LBNL-2001339

ERNEST ORLANDO LAWRENCE
BERKELEY NATIONAL LABORATORY

Analysis of Space-Conditioning Loads in Commercial Buildings

Katie Coughlin, Edward Cubero, Akhil Mathur, and Gregory Rosenquist

Energy Analysis & Environmental Impact Department
Energy Technologies Area
Lawrence Berkeley National Laboratory

June 15, 2020

This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Building Technology, State, and Community Programs, of the U.S. Department of Energy under Lawrence Berkeley National Laboratory Contract No. DE-AC02-05CH1131.

Disclaimer

Acknowledgements

The authors would like to thank Lixing Gu for generating the EnergyPlus simulation data.

Table of Contents

List of Figures

List of Tables

1. *Introduction*

Space conditioning end-uses, which include heating, cooling, and ventilation, represent a significant fraction of commercial building energy use, with a wide variety of heating and cooling technology options available in the market. In the interest of improving the overall efficiency of heating, ventilation and air-conditioning (HVAC) technologies, governments, utilities and private sector entities have implemented a variety of market transformation policies that aim to influence consumer purchase decisions. To evaluate the costs and benefits of such programs, analysts typically postulate a hypothetical default equipment choice, and compare it to one that provides comparable service with lower energy and/or power use. The corresponding reduced operating cost provides a benefit that offsets the potential higher cost of improved efficiency. Typically, life-cycle cost or cash-flow analyses are used to quantify the net economic benefit. These analyses require the capability to assess how a given equipment design would perform across a broad range of characteristics, both of the building and of the local weather. While these assessments can be performed using customized building simulations, it is generally not practical to develop and validate detailed building simulation code to cover all the potential variations of equipment design and installation.

An alternative, and somewhat simpler, approach is to solely use detailed building simulations to generate time series of heating and cooling loads in commercial buildings. These loads can then be used as input to more detailed, stand-alone engineering models that simulate HVAC system performance under different equipment designs. This approach was used to evaluate a range of high-efficiency commercial packaged air conditioner design options for the Department of Energy's Appliance and Equipment Standards Program (DOE-EERE 2015). While there may be some loss of precision relative to full simulation, the accuracy of this approach is sufficient for practical applications of cost-benefit analysis.

This report describes the development of a database of commercial building heating and cooling loads, generated using the EnergyPlus software package, a whole building energy use model supported by the Department of Energy (DOE-EERE 2020a). EnergyPlus takes as input a set of configuration files that describe the building itself (size, zoning, envelope characteristics, etc.) and the various systems within it (HVAC, lighting, water heating, etc.). This analysis uses a publicly available collection of commercial reference buildings (CRB), comprised of sixteen building types and three vintages (DOE-EERE 2020b; Deru et al 2011). Each building is simulated in eighteen different locations, covering a wide range of climatic conditions. The prototype building description files assign the type of HVAC equipment used, and capacities across climate zones.

As described in the next section, this analysis uses EnergyPlus output to disaggregate the HVAC loads into latent and sensible components, and to separate the relative contributions from incoming ventilation air vs. air recirculated from the conditioned zones. This disaggregation reflects the fact that there are different physical drivers for these component loads. Therefore, it should be possible to construct simple correlation models relating building and climate variables to the component loads that are more accurate than such estimates of the total load. This aspect of the problem will be explored in a second report, which will describe how the HVAC loads can be modified to represent alternative assumptions about building envelope characteristics, internal loads, and climate variables.

1.1. Overview of methodology

EnergyPlus represents a building as a set of zones that are served by a specific HVAC system. The systems in the CRB data set cover a wide range of technologies including packaged single-zone systems, chillers, unitary packaged equipment, among others. EnergyPlus represents the functional units of the HVAC equipment through a series of *nodes*; examples include: the cooling coil, the heating coil, and the ventilation fan. Conceptually, this analysis defines an air loop for the system as the path taken by a packet of air as it passes each node in the HVAC system, travels to the conditioned space through the supply duct, and then returns to the HVAC system where it is mixed with outdoor air before beginning the next loop. At each node, EnergyPlus determines the physical air conditions as a function of the heat added or removed by the HVAC system components and/or zonal loads.

The HVAC load database is built from EnergyPlus output consisting of 10-minute time series of the mass flow, air conditions (dry-bulb temperature, humidity ratio, and heat capacity) and other relevant data, for each system in the building, for a full year. These data are collected at the minimum set of nodes needed to fully describe the energy, moisture and mass balance relations around the air loop formed by the system and the zones that it serves.

While both heating and cooling operations are considered in this report, most of the effort is directed towards the understanding of cooling loads, which are more complex due to the presence of latent loads. The air circulating in a building consists of dry air plus a certain quantity of water vapor. When heat is added to an air packet, the temperature changes, but the amount of water vapor in the air is not affected. When heat is removed from an air packet, if the temperature drop is large enough, some moisture will condense out. When the water vapor condenses, it releases energy, which acts as an additional load on the HVAC system. This energy, or heat of vaporization, is referred to as the latent load. The temperature change without a change in moisture content is referred to as the sensible load.

Almost all the HVAC systems modeled in the CRB set are controlled based on the dry-bulb temperature in the conditioned space (the only exceptions are operating rooms in the hospital and outpatient prototypes). With no direct control of humidity, removal of moisture from the incoming ventilation air is an important function of the HVAC system in humid climates. It is expected that the magnitude of the latent load, and corresponding HVAC energy use, to depend primarily on local climate conditions and on building characteristics that correlate with occupancy.

As noted above, to more fully understand the drivers on HVAC loading and energy use, this analysis separates the total space conditioning loads into four components: the latent and sensible loads, and the portion of each associated with outdoor air vs. the air recirculated from the conditioned space. The disaggregation is performed using basic thermodynamic equations and the air conditions reported by EnergyPlus, as described in Section 3. The loads are calculated for each system within a building, which allows comparisons of similar systems across both building types and climate zones.

While thermodynamics allows the *loads* to be separated into latent and sensible components, the HVAC system deals with both simultaneously, so understanding how the system *energy use* depends on latent vs. sensible load is more complicated. In this paper, data are used for the same building and system across different climates to estimate the relative importance of latent loads to overall energy use. The time-series data are binned according to the value of outdoor dry-bulb temperature and humidity ratio. Within a single dry-bulb temperature bin, the variation of energy use with humidity ratio provides an estimate of the importance of latent loads to overall energy use. The goal of this initial analysis is to provide a general picture of the relative importance of latent vs. sensible loads, and of the contribution of outdoor ventilation air to the loads and related energy consumption. A second report will describe how the load database assembled here can be used to develop estimates of potential impacts on energy use of equipment design changes, changes to the building envelope, or changes to climate conditions.

1.2. Outline of this report

Section 2 provides a description of the climate zones and the commercial reference buildings used in this analysis, including a summary of the zone layout and the HVAC system characteristics for each building. It also provides a schematic description of the organization of system nodes, and identify the specific EnergyPlus output variables that are used here to describe the air loop. Section 3 presents the mass and energy balance equations, with latent and sensible loads treated separately. It also identifies the contribution to the loads from incoming outdoor air vs. the air recirculated from the zones. Section 4 validates the approach presented by comparing the loads calculated from air conditions to those directly reported by EnergyPlus. The results and discussion are presented in Section 5.

2. Summary of Energy Plus Buildings and Output

This section provides a summary of the building prototypes, the climate zones and representative cities, and the heating and cooling systems in the modeled buildings. It also provides a schematic description of the arrangement of nodes for each system type, and the selection of nodes and output variables used in this analysis.

2.1. Building prototypes and climate zones

2.1.1. Commercial Reference Buildings

The Department of Energy (DOE) has developed building prototypes, referred to as the DOE Reference Buildings, which are meant to be used to model annual HVAC energy use in

EnergyPlus (Deru et al 2011). The DOE Commercial Reference buildings represent common building types in the U.S. commercial building stock and consist of 16 buildings (15 commercial buildings and one multifamily residential building) in three vintages: pre-1980, post-1980, and new construction. The 16 buildings and three vintages represent approximately two thirds of the U.S. commercial building stock. The three vintages have the same area and operating schedules, the differences are found in building characteristics such as insulation, lighting, HVAC equipment efficiency. As reported in Deru at al 2011, Table 2-1 below displays the 16 building types and their square footage.

Table 2-1 Commercial Building Prototypes

		Cooling Capacity *(tons per sq. ft.)*		
Building Type	**Square Footage**	**Chicago**	**Houston**	**Phoenix**
Small Office	5,500	0.0018	0.0020	0.0020
Medium Office	53,628	0.0023	0.0024	0.0025
Large Office	498,588	0.0018	0.0019	0.0019
Primary School	73,960	0.0020	0.0022	0.0022
Secondary School	210,887	0.0031	0.0033	0.0030
Stand-Alone Retail	24, 692	0.0022	0.0025	0.0023
Strip Mall	22,500	0.0021	0.0025	0.0024
Supermarket	45,000	0.0034	0.0029	0.0028
Quick Service Restaurant	2,500	0.0054	0.0055	0.0055
Full Service Restaurant	5,500	0.0047	0.0048	0.0048
Small Hotel	43,200	0.0018	0.0019	0.0020
Large Hotel	122,120	0.0017	0.0018	0.0016
Hospital	241,351	0.0034	0.0037	0.0034
Outpatient Healthcare	40,946	0.0036	0.0038	0.0039
Warehouse	52,045	0.0008	0.0007	0.0007
Midrise Apartment	33,740	0.0017	0.0016	0.0017

Representativeness of Commercial Reference Buildings of the U.S. Building Stock

To further investigate how representative the CRB dataset is of the full building stock, the 2012 Commercial Building Energy Consumption Survey (CBECS) data (DOE-EIA 2012) and commercial floor-space projections from the Annual Energy Outlook (AEO) 2020 (DOE-EIA 2020) are used to estimate the distribution of floor-space by building type and vintage category in the year 2020. As shown below in Table 2-2, the three vintage categories are Pre-1980, 1980-2003, 2004-2012, and 2013 to 2020. The AEO Commercial Demand Module documentation (DOE-EIA 2014) provides an algorithm for retiring building floor-space, which was applied to the CBECS 2012 data to estimate the quantity of floor-space in that survey that would have been taken out of the building stock by 2020. The AEO 2020 projection of new construction for the years 2013-2020 was then used to populate the vintage category 2013-2020. The results are summarized in Table 2-2. The sixth column of this table shows the percent of all floor-space allocated to that building type, and the seventh column lists the CRB prototypes that map to that building type. Note the AEO maps outpatient healthcare buildings to their small and large office categories. Small office corresponds to building floor-space less than or equal to 50,000 square feet.

Table 2-2 Distribution of Commercial Floor-space by Vintage in 2020

Building Type	Vintage Category: Pre-1980	1980-2003	2004-2012	2013-2020	Percent of Floor-space in 2020	Prototypes
Assembly	48%	31%	11%	10%	11%	None available
Education	43%	30%	12%	14%	14%	Primary school, Secondary school
Food Sales	35%	37%	16%	12%	1%	Supermarket
Food Service	44%	34%	9%	13%	2%	Full-service Restaurant, Quick-service Restaurant
Health Care	44%	22%	17%	17%	3%	Hospital
Lodging	33%	37%	12%	19%	7%	Small Hotel, Midrise Apartment, Large Hotel
Large Office	39%	44%	7%	11%	10%	Large Office, Medium Office
Small Office	39%	37%	12%	12%	10%	Small Office, Outpatient
Mercantile/Services	33%	39%	14%	15%	18%	Stripmall, Stand-alone Retail
Warehouse	31%	37%	16%	15%	15%	Warehouse
Other	44%	34%	8%	14%	8%	None available
All Buildings	**38%**	**36%**	**12%**	**14%**	**100%**	

The 'Assembly' (theatres, churches, etc.) and 'Other' AEO commercial building categories are not included in the CRB prototypes. About 50% of the 'Other' category refers to vacant buildings, most of which presumably would be represented by the existing prototypes if they were occupied. Hence, about 15% of all floor-space does not have a corresponding prototype.

It seems reasonable to assume that the Pre-1980 and 1980-2003 vintage categories are well-represented by the Pre-1980 and Post-1980 vintage prototypes. These vintages represent 74% of total floor-space. The New vintage prototype corresponds to ASHRAE 90.1-2004 code requirements published in 2004, and it is likely that some fraction of buildings constructed after 2004 are designed to more recent codes. The magnitude of this fraction depends both on what building code was current in the year of construction, and what the code compliance rate is.

State-by-state building code adoption data are available from the U.S. Department of Energy's Building Energy Codes Program (DOE-BECP 2019) for December 2019. Based on these data, as of December 2019, states representing 19 percent of the US population have a building code more stringent than ASHRAE 90.1 2013, 42 percent have codes equal to ASHRAE 90.1-2013, 7 percent have codes equal to ASHRAE 90.1-2010, 20% have codes equal to ASHRAE 90.1-2007, and 11 percent have codes less stringent than ASHRAE 90.1-

2007 or have no statewide code. Roughly, from this it is inferred that about 80 percent of the population is in states having codes that are more than five years out of date, and 20 percent is states with codes adopted within the last few years. Based on this breakdown, of the 12% of building floor-space in vintage category 2004-2012, roughly 9% would be subject to codes comparable to 2004 (i.e. codes 5 or more years out-of-date in 2012). The remainder, plus the floor-space in the 2013-2020 category, leads to an estimate of 17% of floor-space that might be subject to more stringent codes than are represented in the CRB prototypes.

Adoption rates do not necessarily reflect compliance. Enforcing code compliance can be expensive, and an extensive review of available data has indicated widely varying compliance rates (Williams et al. 2013). Many states lack sufficient data to estimate compliance. Hence, a 50% compliance rate across all states was assumed. Thus, of the 17% of floor-space potentially subject to more stringent codes, it is assumed that about 9% are compliant; rounding to one digit of precision, this estimate suggests that about 10% of floor-space would comply with codes more stringent than the "New" prototype.

In summary, these estimates suggest that about 15% of floor-space does not have a CRB prototype, and about 10% of floor-space may be subject to more stringent codes than are modeled in the CRB prototypes. While these are upper bounds based only on building and vintage category, they do indicate that about 75% of floor-space is at least in the general categories modeled by the CRB prototypes.

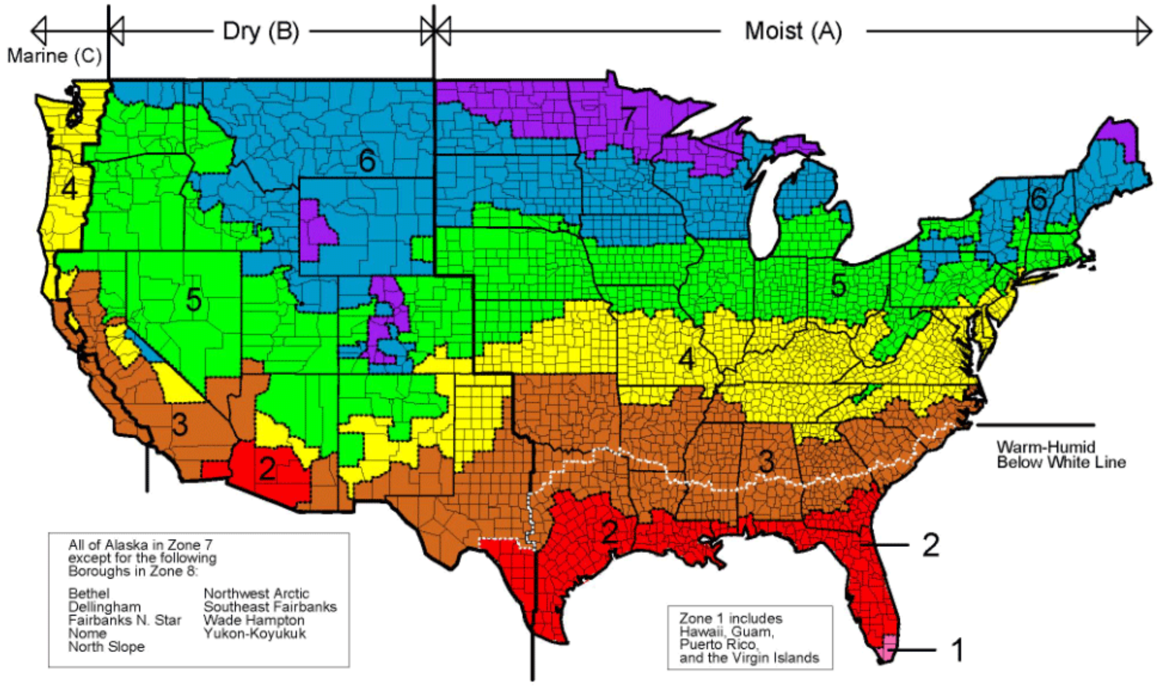
2.1.2. Climate Zones

The climate zones used in Deru et al 2011 were based on based on Briggs et al 2003, which developed climate zones for DOE and ASHRAE 2004 (Briggs et al 2003). As shown below in Figure 2-1, these climate zones consist of eight areas across the U.S., in mostly east-west bands with zone one being the southernmost and zone eight, which is not pictured as its location is solely in Alaska, being the northernmost part of the country. The U.S. is also divided into vertical subdivisions: moist (A), dry (B), and marine (C). In total there are 16 climate zones as shown in Source: Figure 1 Climate zone classification (Deru at al 2011)

Figure 2-1 below.

2.1.3. Representative Cities

Deru et al 2011 chose a representative city which balanced the representativeness of the climate and the number of buildings in each climate zone. The representative city weather file is used to simulate the hourly weather over the course of a typical meteorological year (TMY) for each building's simulation. The TMY data consist of individual calendar months of historic data, chosen from years which represent median or average weather; hence, TMY data do not include more extreme weather events such as heat or cold waves. Table 2-3 displays the 16 climate zones and the representative cities used for weather data.



Source: Figure 1 Climate zone classification (Deru at al 2011)

Figure 2-1 Climate Zone Classification

Table 2-3 Climate Zones and Representative Cities

Climate Zone	Climate Type	Representative City
1A	Hot-Humid	Miami, FL
2A	Hot-Humid	Houston, TX
2B	Hot-Dry	Phoenix, AZ
3A	Hot-Humid / Mixed-Humid	Atlanta, GA
3B – CA	Hot-Dry	Los Angeles, CA
3B – other	Hot-Dry	Las Vegas, NV
3C	Marine	San Francisco, CA
4A	Mixed-Humid	Baltimore, MD
4B	Mixed-Dry	Albuquerque, NM
4C	Marine	Seattle, WA
5A	Cold	Chicago, IL
5B	Cold	Boulder, CO
6A	Cold	Minneapolis, MN
6B	Cold	Helena, MT
7	Very Cold	Duluth, MN
8	Subarctic	Fairbanks, AK

Source: Table 2 Selected Commercial Reference Building Model Locations (Deru at al 2011)

2.1.4. Summary of Each Commercial Reference Building

Below is a summary of the new construction vintage of the 16 reference buildings. Table 2-4 at the end of this section summarizes the characteristics of each building.

Small Office

The small office building is a rectangular, one floor building consisting of five zones: a core zone and four perimeter zones. Each zone is served by a packaged single zone (PSZ) unit with a direct-expansion (DX) coil for air conditioning and a gas furnace for heating. Economizers are not used in the small office prototype building.

Medium Office

The medium office building is a rectangular, three story building with five zones per floor: a core zone and four perimeter zones. For new construction and post-1980 buildings, each floor is served by a packaged variable air volume (VAV) system, with a DX-coil for air-conditioning, zone-level electric reheat coils, and a gas furnace for heating. Differential dry bulb economizers are used in all climate zones except for the hot-humid zones (1A, 2A, 3A, and 4A). The floor plan and occupancy do not change by floor.

Large Office

The large office is a rectangular, twelve story building with five zones per floor: a core zone and four perimeter zones, as well as a single-zone basement. The building has a two chillers and a boiler which serve a VAV system on each floor and the basement. Each zone except for the basement has electric reheat coils. Differential dry bulb economizers are used in all climate zones except for the hot-humid zones (1A, 2A, 3A, and 4A). The floor plan and occupancy do not change by floor.

Primary School

The primary school is a one floor building in the shape of the letter "E", composed of three pods which contain the classrooms, and a main building with a gym, cafeteria, kitchen, library, offices, lobby, bathrooms, and a main corridor. Each pod consists of 5 zones, with 4 classrooms and a corridor zone. Each pod and the main building is served by a packaged VAV system, with a DX coil for air-conditioning, zone level electric reheat coils, and a boiler for heating. The gym, cafeteria, and kitchen are each served by their own packaged single zone rooftop unit with a DX-coil for cooling and a gas furnace for heating.

Secondary School

The secondary school building is a two floor building in the shape of the letter "E", composed of three two-floor pods which contain classrooms, a two-floor main building with a lobby, offices, a library, bathrooms, and a main corridor, and two gyms, a cafeteria, a kitchen, and an auditorium. Each pod and the main building are served by a chiller and boiler with a VAV air distribution system with electric reheat in each zone. The two gyms, the auditorium, cafeteria, and kitchen are single zones, each served by their own packaged single zone rooftop unit with a DX-coil for cooling and a gas furnace for heating.

Stand Alone Retail

The stand-alone retail building is a rectangular, one floor building with four conditioned zones: the point of sale area, the front retail area, a large core retail zone, and a back zone. Each zone is served by a packaged single zone rooftop unit with a DX-coil for cooling and a gas furnace for heating. Differential dry bulb economizers are used in the core retail zone in all climate zones except for the hot-humid zones (1A, 2A, 3A, and 4A). The back space zone uses an economizer in climate zones 4B, 5B, 6B, and 7.

Strip Mall

The strip mall building is a rectangular, one floor building consisting of two large stores and eight smaller stores which are all connected. One large store is located at the end of the building, followed by four small stores, another large store, and four more small stores. Each store is a single zone and served by a packaged single zone rooftop unit with a DX coil for cooling and a furnace for heating. Differential dry bulb economizers are used in large store 1 in climate zones 3B, 3C, 4B, 4C, 5B, and 6B and large store 2 in climate zones 3B and 4B.

Supermarket

The supermarket building is a rectangular, one floor building consisting of six zones: sales, produce, dry storage, deli, bakery, and offices. Each zone is served by a packaged single zone unit with a DX-coil for cooling and a gas furnace for heating. Differential dry bulb economizers are used in the dry storage, sales, and produce zones in all climate zones except for the hot/mixed-humid zones (1A, 2A, 3A, and 4A).

Quick Service Restaurant

The quick service restaurant building is a square, one floor building consisting of two equally sized conditioned zones. Each zone is served by a packaged single zone rooftop unit with a DX coil and a furnace to provide cooling and heating. Differential dry bulb economizers are used in the dining room in climate zones 3B, 3C, 4B, 4C, 5B, and 6B.

Full Service Restaurant

The full service restaurant building is a square, one floor building consisting of two zones, a larger dining room and a smaller kitchen. Each zone is served by a packaged single zone rooftop unit with a DX coil for cooling and a furnace for heating. Differential dry bulb economizers are used in all climate zones except for the hot/mixed-humid zones (1A, 2A, 3A, and 4A).

Warehouse

The warehouse reference building is a rectangular, one floor building with three zones: offices, a fine storage area, and a bulk storage area. The offices and the fine storage zones are each served by a unitary packaged precision air cooled unit with a DX-coil for cooling and a gas furnace for heating. The bulk storage area is not cooled, but has a gas fired unit heater coil to provide heating. Differential dry bulb economizers are used in all climate zones except for the hot/mixed-humid zones (1A, 2A, 3A, and 4A) in the fine storage area, and climate zones 4B, 5B, and 6B in the office zone.

Large Hotel

The large hotel is a rectangular, 6 floor building with a basement. The first floor of the hotel consists of a lobby, a café, laundry, a mechanical room, a storage room, and two retail spaces. The remaining five floors consist of hotel rooms. Floors two through five have 42 guest rooms, the sixth floor has 11 guest rooms along with a banquet hall and a restaurant. The hotel is served by two chillers for air conditioning and a boiler for heating. A VAV distribution system with electric zone reheat is used for the first floor, the restaurant, and the banquet hall. A dedicated outside air system is used to provide ventilation for the guest rooms and each guest room has a fan coil for cooling and heating within the room. The VAV zones use a differential dry bulb economizer in all climate zones except for the hot/mixed-humid zones (1A, 2A, 3A, and 4A).

Small Hotel

The small hotel is a rectangular, four floor building with 77 guest rooms. Each guest rooms is served by a PTAC with a DX-coil for cooling and an electric individual space heater for heating. There are 12 packaged single zone units with a DX-coil for cooling and a gas furnace for heating, that serve the common spaces of the hotel: corridors, lounges, meeting rooms, laundry rooms, offices, and the exercise center. A differential dry bulb economizer is used in the laundry room in climate zones 3B, 3C, 4B, 4C, 5B, and 6B.

Hospital

The hospital is a rectangular, five floor building with a basement. The hospital consists of an emergency room, an intensive care unit, operating rooms, patient rooms, physical therapy, offices, a lobby, labs, nurse's stations, a dining hall, kitchen, and conditioned corridors. The hospital is served by a chiller for air conditioning and a boiler for heating. A CAV air distribution system is used for the emergency room, operating rooms, the intensive care unit, and some patient rooms. The remainder of the hospital uses a VAV air distribution system with electric reheat. The VAV zones use a differential dry bulb economizer in all climate zones except for the hot/mixed-humid zones (1A, 2A, 3A, and 4A).

Outpatient Healthcare

The outpatient healthcare building is irregular shaped and three floors. The outpatient healthcare building consists of exam rooms, offices, a lobby, waiting rooms, pre-operating room, operating rooms, storage, restrooms, physical therapy, and staff lounges. The building is served by two packaged variable air volume systems, with a DX-coil for air-conditioning and a boiler for heating. Each zone has a VAV box with electric reheat coils. A differential dry bulb economizer is used in all climate zones except for the hot/mixed-humid zones (1A, 2A, 3A, and 4A).

Midrise Apartments

The midrise apartment is a rectangular shaped, four floor building. The midrise apartment building consists 31 identical apartments and one office which is the same size as an apartment. Each apartment and the office is served by a separate unitary split system with a DX-coil for air conditioning and a gas furnace for heating.

Summary of Prototype Building Characteristics

As reported in the DOE reference building scorecard spreadsheets, which are available on the DOE reference building website (DOE-EERE 2020b), Table 2-4 displays the characteristics of the 16 prototype buildings. The occupants per zone are not a whole number as they are based on averages from various data sources, which either estimate an average number of people per space (such as a hotel room) or the square footage per occupant for a specific building type. More details on the occupancy of the prototype buildings can be found in Deru et al 2011. Each prototype building is assigned an operating schedule for end use equipment. As noted earlier, almost all the HVAC systems modeled in the CRB set are controlled based on the dry-bulb temperature in the conditioned space (exceptions are noted below). In most cases, there is a weekday and a weekend operating schedule, which does not change by climate zone. The operating schedules can be found in the DOE reference building scorecard spreadsheets.

Table 2-4 Prototype Building Characteristics

Building	Zone	Square footage	People	Lights *(W/sq. ft.)*	Plug and Process *(W/sq. ft.)*	Ventilation *(cfm)*	Cooling Setpoint *(°F)*	Heating Setpoint *(°F)*
Small Office	Core	1,611	8.05	1	1	171	75.2	69.8
	Perimeter 1	1,221	6.11	1	1	129	75.2	69.8
	Perimeter 2	724	3.62	1	1	77	75.2	69.8
	Perimeter 3	1,221	6.11	1	1	129	75.2	69.8
	Perimeter 4	724	3.62	1	1	77	75.2	69.8
Medium Office	Core*	10,587	52.93	1	1	1,122	75.2	69.8
	Perimeter 1*	2,232	11.16	1	1	236	75.2	69.8
	Perimeter 2*	1,413	7.06	1	1	150	75.2	69.8
	Perimeter 3*	2,232	11.16	1	1	236	75.2	69.8
	Perimeter 4*	1,413	7.06	1	1	150	75.2	69.8
Large Office	Basement	38,353	95.88	1	1	2,032	75.2	69.8
	Core**	27,258	136	1	1	2,888	75.2	69.8
	Perimeter 1**	3,374	16.87	1	1	357	75.2	69.8
	Perimeter 2**	2,174	10.87	1	1	230	75.2	69.8
	Perimeter 3**	3,374	16.87	1	1	357	75.2	69.8
	Perimeter 4**	2,174	10.87	1	1	230	75.2	69.8
Primary School	Pod 1	14,467	307.20	1.27	1.25	5,085	75.2	69.8
	Pod 2	14,467	307	1.27	1.25	5,085	75.2	69.8
	Pod 3	12,723	266.70	1.25	1.23	4,399	75.2	69.8
	Main building	23,261	161.89	1.05	0.80	4,375	75.2	69.8
	Gym	3,843	107.21	1.40	0.46	2,272	75.2	69.8
	Kitchen	1,808	25.19	1.20	17.70	427	75.2	69.8

Building	Zone	Square footage	People	Lights *(W/sq. ft.)*	Plug and Process *(W/sq. ft.)*	Ventilation *(cfm)*	Cooling Setpoint *(°F)*	Heating Setpoint *(°F)*
	Cafeteria	3,391	226.04	1.40	2.36	4,790	75.2	69.8
Secondary School	Pod 1	31,689	640	12.24	10.22	10,442	75.2	69.8
	Pod 2	31,689	640	12.24	10.22	10,442	75.2	69.8
	Pod 3	31,689	640	12.24	10.22	10,442	75.2	69.8
	Main building	61,440	295	10.09	5.91	8,895	75.2	69.8
	Gym	34,703	2,392	15.07	5.00	50,684	75.2	69.8
	Auditorium	10,635	988	9.69	5.00	16,748	75.2	69.8
	Kitchen	2,325	36	12.92	222.27	610	75.2	69.8
	Cafeteria	6,717	449	15.07	19.27	9,512	75.2	69.8
Stand-Alone Retail	Back Space	4,089	13.63	0.8	0.75	604	75.2	69.8
	Core Retail	17,227	258.40	1.7	0.3	5,087	75.2	69.8
	Point of Sale	1,623	24.35	1.7	2	479	75.2	69.8
	Front Retail	1,623	24.35	1.7	0.3	479	75.2	69.8
	Front Entry	129	1.94	1.1	0	0	75.2	69.8
Strip Mall	Large Store 1	3,750	56.25	11.33	2.03	523	75.2	69.8
	Small Store 1	1,875	28.12	11.33	2.03	261	75.2	69.8
	Small Store 2	1,875	28.12	8.64	2.03	261	75.2	69.8
	Small Store 3	1,875	28.12	8.64	2.03	261	75.2	69.8
	Small Store 4	1,875	28.12	8.64	2.03	261	75.2	69.8
	Large Store 2	3,750	56.25	6.50	2.03	523	75.2	69.8
	Small Store 5	1,875	28.12	6.50	2.03	261	75.2	69.8
	Small Store 6	1,875	28.12	6.50	2.03	261	75.2	69.8
	Small Store 7	1,875	28.12	6.50	2.03	261	75.2	69.8
	Small Store 8	1,875	28.12	6.50	2.03	261	75.2	69.8
Super-market	Office	956	4.78	1.10	0.75	101	75.2	69.8
	Dry Storage	6,694	22.31	0.80	0.75	988	75.2	69.8
	Deli	2,419	19.35	1.70	5.00	714	75.2	69.8
	Sales	25,025	200.20	1.70	0.50	7,389	75.2	69.8
	Produce	7,657	61.26	1.70	0.50	2,261	75.2	69.8
	Bakery	2,250	18.00	1.70	5.00	664	75.2	69.8
Quick Service Restaurant	Dining	1,250	83.33	2.1	12	393	75.2	69.8
	Kitchen	1,250	6.25	1.2	28	24	78.8	66.2
Full Service Restaurant	Dining	4,001	266.77	2.1	5.6	1,259	75.2	69.8
	Kitchen	1,501	7.50	1.2	35	28	78.8	66.2
Warehouse	Office	2,550	5.00	1.1	0.75	24	75.2	69.8
	Fine Storage	14,999	0.00	1.4	0	164	80	60.8
	Bulk Storage	34,497	0.00	0.9	0.25	378	0	45
Large Hotel	Basement and Floor 1	42,600	640	1.1	0.7	3,035	75.2	69.8
	Guest Rooms	68,888	290	0.9	0.9	1,428	75.2/86†	69.8/60.8†
	Banquet & Restaurant	8,252	482	1.3	11.8	2,267	75.2	69.8
Small Hotel	Guestrooms	27,758	765.91	1.10	1.3	2,310	75.2	69.8

Building	Zone	Square footage	People	Lights *(W/sq. ft.)*	Plug and Process *(W/sq. ft.)*	Ventilation *(cfm)*	Cooling Setpoint *(°F)*	Heating Setpoint *(°F)*
	Corridor - FLR 1	1,620	0.00	0.50	0.0	80	75.2	69.8
	Corridor - FLR 2	1,350	0.00	0.50	0.0	66	75.2	69.8
	Corridor - FLR 3	1,350	0.00	0.50	0.0	66	75.2	69.8
	Corridor - FLR 4	1,350	0.00	0.50	0.0	66	75.2	69.8
	Front Lounge	1,755	52.71	1.10	1.4	893	75.2	69.8
	Front Office	1,404	10.03	1.10	1.2	212	75.2	69.8
	Restroom	351	1.00	0.90	1.0	0	75.2	69.8
	Meeting Room	864	43.20	1.30	1.2	915	75.2	69.8
	Mechanical Room	351	0.00	1.50	0.0	17	75.2	69.8
	Employee Lounge	351	10.54	1.20	7.2	179	75.2	69.8
	Laundry Room	1,053	10.53	0.60	2.0	290	75.2	69.8
	Exercise Center	351	10.54	0.90	1.1	223	75.2	69.8
Hospital	CAV 1	18,900	157	1.2	2.1	1,565	72	70
	CAV 2	8,250	41	1.9	4.4	3,711	72/65◊	70/65◊
	VAV 1	109,298	472	1.1	0.9	26,713	72	70
	VAV 2	104,902	620	1.0	2.0	42,284	72	70
Outpatient Health Care	Floor 1	14,186	175	1.1	3.4	4,381	72/65◊	70/65◊
	Floor 2 and 3	26,760	224	1.0	0.9	4,248	72	70
Midrise Apartment	Apartment^	950	2.50	0.4	0.5	90	75	70
	Office	950	2.00	1.2	6.1	42	75	70

* Medium Office has three floors. Multiply Core and Perimeter zones by three to obtain total square footage.
** Large Office has twelve floors. Multiply Core and Perimeter zones by twelve to obtain total square footage.
^ Midrise Apartment has 31 apartments. Multiply Apartment zone by 31 to obtain total square footage.
† This is the setpoint temperature for the guest room corridors.
◊ This is the operating room temperature.

2.2. System types

As reported in the DOE reference building scorecard spreadsheets, which are available on the DOE reference building website (DOE-EERE 2020b), Table 2-5 summarizes the HVAC systems used in each building. For each HVAC system, the fan-type is specified as a draw-through or blow-through, both of which are described in Section 2.3.

Table 2-5 HVAC System types for Prototype Buildings

Building Type	HVAC Type*	Zones	Cooling#	Heating	Fan Type	Reheat	Economizer**
Small Office	PSZ	5	DX	Gas Furnace	Draw-through	No	No
Medium Office	MZ_VAV	15	DX	Gas Furnace	Draw-through	Yes	Yes
Large Office	MZ_VAV	61	Chiller	Boiler	Draw-through	Yes	Yes
Primary School	MZ_VAV	22	DX	Boiler	Draw-through	Yes	Yes
	PSZ	3	DX	Gas Furnace	Draw-through	No	Yes
Secondary School	MZ_VAV	41	Chiller	Boiler	Draw-through	Yes	Yes
	PSZ	5	DX	Gas Furnace	Draw-through	No	Yes
Stand Alone Retail	PSZ	4	DX	Gas Furnace	Blow-through	No	Yes
Strip Mall	PSZ	10	DX	Gas Furnace	Blow-through	No	Yes
Supermarket	PSZ	6	DX	Gas Furnace	Draw-through	No	Yes
Quick Service Restaurant	PSZ	2	DX	Gas Furnace	Draw-through	No	Yes
Full Service Restaurant	PSZ	2	DX	Gas Furnace	Draw-through	No	Yes
Warehouse	PSZ	3	DX	Gas Furnace	Blow-through	No	Yes
Large Hotel	MZ_VAV	16	Chiller	Boiler	Draw-through	Yes	Yes
	Fan Coil	179	Chiller	Boiler	Draw-through	No	No
	DOAS	179	Chiller	Boiler	Draw-through	No	No
Small Hotel	PTAC	77	DX	Elec. Resistance	Draw-through	No	No
	PSZ	12	DX	Gas Furnace	Draw-through	No	No
Hospital	MZ_CAV	93	Chiller	Boiler	Draw-through	No	No
	MZ_VAV	68	Chiller	Boiler	Draw-through	Yes	Yes
Outpatient Healthcare	MZ_VAV	118	DX	Boiler	Draw-through	Yes	Yes
Midrise Apartment	Unitary Split System	32	DX	Gas Furnace	Blow-through	No	No

* **HVAC Types:** PSZ = package single zone; MS_VAV = multi-zone system, variable air volume; MS_CAV = multi-zone system, constant air volume; DOAS = dedicated outdoor air system; PTAC = packaged terminal air conditioner.

Cooling: DX = direct-expansion.

Economizer: Economizers are not used in climate zones 1A, 2A, 3A, and 4A.

2.3. System nodes and system variables

Each heating, ventilating, and air-conditioning (HVAC) system is defined as:

x = the index of the HVAC system,
$Type_x$ = the type of system x,
N = number of HVAC systems in the building, so $x = 1, \ldots N$.

An HVAC system may serve multiple zones; the total zones served by system, x, is:

n_x = number of zones being served by HVAC system, *x*.
For each HVAC system, *x*, there are the following system nodes:

ra_x = return air,
rfa_x = relief air,
oa_x = outdoor air,
ma_x = mixed air inlet,
cc_x = cooling coil inlet (same as the ma_x node in a draw-through system),
hc_x = heating coil inlet,
sf_x = supply fan inlet (same as the ma_x node in a blow-through system), and
sa_x = supply air.

Figure 2-2 depicts an HVAC system and the zones it serves. Two types of HVAC systems are depicted in Figure 2-2; a draw-through system, where the supply fan draws the mixed air through the cooling and heating coils, and a blow-through system, where the supply fan draws in mixed air and then blows it through the cooling and heating coils. The system nodes are labeled to show their location within the HVAC system. As noted in Figure 2-2, the supply air delivered to each zone may pass through a reheat coil in order to condition the air before it is delivered to the zone. Finally, some of the air from a zone may be exhausted, either through the relief air node, or (for kitchens and laundry) directly though a zonal exhaust node; the zone air that is not exhausted is returned back to the HVAC system to be reconditioned. Table 2-6 summarizes the variable names of each air property at each system node.

The HVAC system nodes are indexed by the letter *j*. At each node, *j*, of system *x*, there are the following air properties:

$\dot{m}_{j\_x}$ = mass flow rate (kg/s),
T_{j_x} = dry-bulb temperature (°C),
$c_{p\_j\_x}$ = specific heat (kJ/kg-°C),
$w_{kg\_j\_x}$ = humidity ratio (kg_{water} /$kg_{dry\ air}$), and
$v_{we\_j\_x}$ = latent heat of vaporization (kJ/kg).

Table 2-6 HVAC System Node and System Air Property Variable Names

	System Air Property				
System Node	**Mass Flow Rate**	**Dry-Bulb Temperature**	**Specific Heat**	**Humidity Ratio**	**Latent Heat of Vaporization**
Return Air	$\dot{m}_{ra\_x}$	T_{ra_x}	$c_{p\_ra\_x}$	$w_{kg\_ra\_x}$	$v_{we\_ra\_x}$
Relief Air	$\dot{m}_{rfa\_x}$	T_{rfa_x}	$c_{p\_rfa\_x}$	$w_{kg\_rfa\_x}$	$v_{we\_rfa\_x}$
Outdoor Air	$\dot{m}_{oa\_x}$	T_{oa_x}	$c_{p\_oa\_x}$	$w_{kg\_oa\_x}$	$v_{we\_oa\_x}$
Mixed Air Inlet	$\dot{m}_{ma\_x}$	T_{ma_x}	$c_{p\_ma\_x}$	$w_{kg\_ma\_x}$	$v_{we\_ma\_x}$
Cool Coil Inlet	$\dot{m}_{cc\_x}$	T_{cc_x}	$c_{p\_cc\_x}$	$w_{kg\_cc\_x}$	$v_{we\_cc\_x}$
Heat Coil Inlet	$\dot{m}_{hc\_x}$	T_{hc_x}	$c_{p\_hc\_x}$	$w_{kg\_hc\_x}$	$v_{we\_hc\_x}$
Supply Fan Inlet	$\dot{m}_{sf\_x}$	T_{sf_x}	$c_{p\_sf\_x}$	$w_{kg\_sf\_x}$	$v_{we\_sf\_x}$
Supply Air	$\dot{m}_{sa\_x}$	T_{sa_x}	$c_{p\_sa\_x}$	$w_{kg\_sa\_x}$	$v_{we\_sa\_x}$

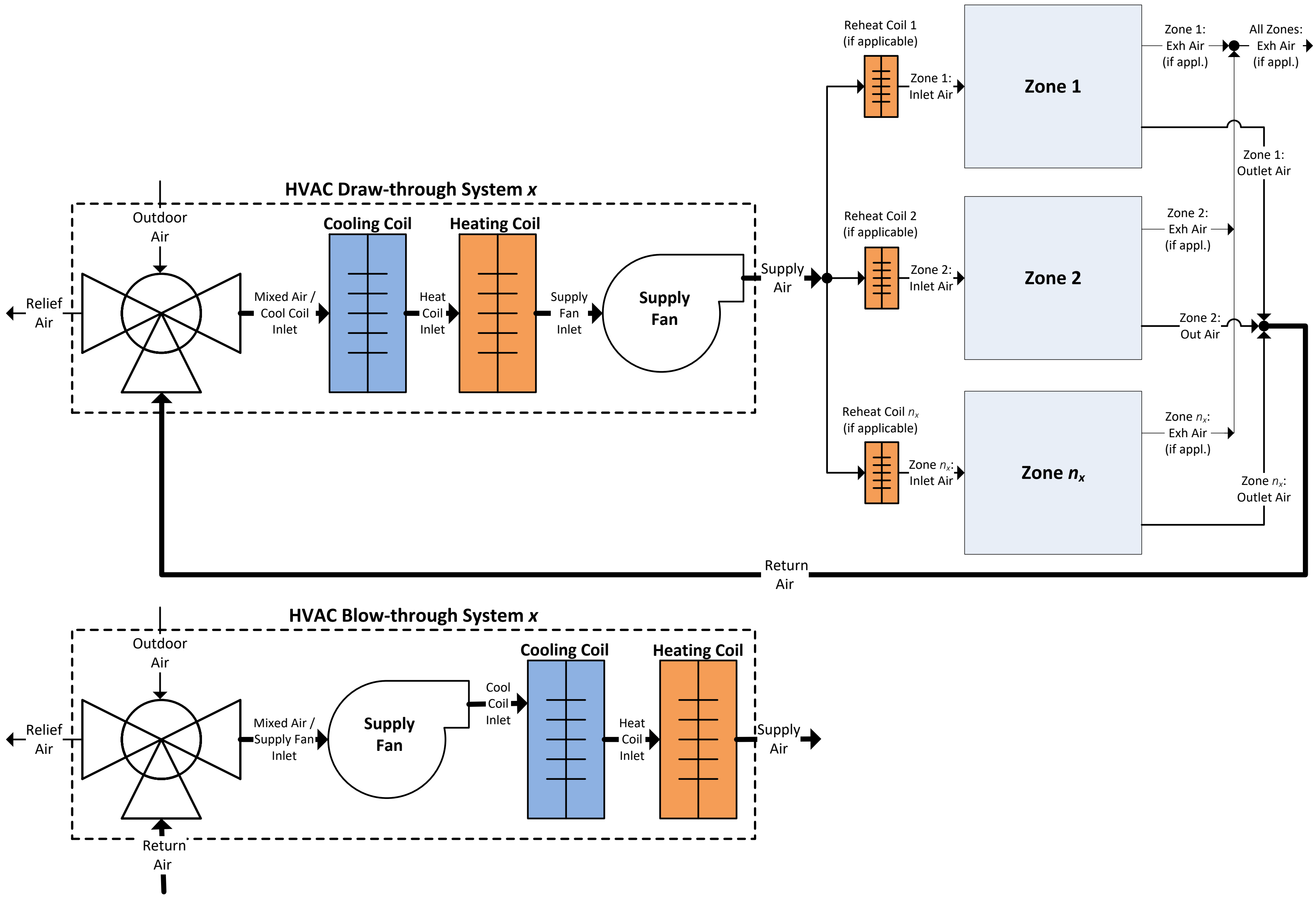


Figure 2-2 Typical HVAC System and Zone Nodes

2.4. Zone definitions and zone variables

All zones in a building that are served by an HVAC system are mapped to one of the N systems in the building. Zone variables are defined by both a zone index, and the index, x, of the HVAC system serving that zone.

The zone index is incremented in steps of 1 up to the number of zones, n_x, served by an HVAC system, x, which is expressed as follows:

z = the index of the zone,
n_x = number of zones being served by HVAC system, x, so $z = 1, \ldots n_x$.

For each zone, z, being served by an HVAC system, x, there are the following nodes:

zi_z = zone inlet,
zm_z = zone mean or location at the center of the zone,
zo_z = zone outlet, and
zex_z = zone exhaust,

The zone nodes are indexed by the letter k. At each node, k, of zone z, there are the following air properties:

$\dot{m}_{k\_z\_x}$ = mass flow rate (kg/s),
$T_{k\_z\_x}$ = dry-bulb temperature (°C),
$c_{p\_k\_z\_x}$ = specific heat (kJ/kg-°C),
$w_{kg\_k\_z\_x}$ = humidity ratio (kg_{water} /$kg_{dry\ air}$), and
$v_{we\_k\_z\_x}$ = latent heat of vaporization (kJ/kg).

Some zones may have an exhaust fan (for example in kitchens); hence, the system air loop may include an additional quantity of air exhausted. The air properties of both the mass flow exhausted out, and that returned to the HVAC system from each zone, z, are similar to the air properties of the zone mean mass flow rate. Table 2-7 illustrates how zones, their associated HVAC system, air properties and mass flow rates are indexed.

Table 2-7 Relationship between number of HVAC systems (x) and corresponding number of Zones (n_x) served by each system with Zone Air Property Variable Names

System No.	Zone No.	Zone Node	Zone Air Property: Mass Flow Rate into Zone	Dry-Bulb Temperature	Specific Heat	Humidity Ratio	Latent Heat of Vaporization
1	1	Zone Inlet	$\dot{m}_{zi\_1\_1}$	$T_{zi\_1\_1}$	$c_{p\_zi\_1\_1}$	$w_{kg\_zi\_1\_1}$	$v_{we\_zi\_1\_1}$
		Zone Mean	$\dot{m}_{zm\_1\_1}$	$T_{zm\_1\_1}$	$c_{p\_zm\_1\_1}$	$w_{kg\_zm\_1\_1}$	$v_{we\_zm\_1\_1}$
		Zone Outlet	$\dot{m}_{zo\_1\_1}$	$T_{zo\_1\_1}$	$c_{p\_zo\_1\_1}$	$w_{kg\_zo\_1\_1}$	$v_{we\_zo\_1\_1}$
		Zone Exhaust	$\dot{m}_{zex\_1\_1}$	$T_{zex\_1\_1}$	$c_{p\_zex\_1\_1}$	$w_{kg\_zex\_1\_1}$	$v_{we\_zex\_1\_1}$
	⋮	⋮	⋮	⋮	⋮	⋮	⋮
	n_1	Zone Inlet	$\dot{m}_{zi\_n_1\_1}$	$T_{zi\_n_1\_1}$	$c_{p\_zi\_n_1\_1}$	$w_{kg\_zi\_n_1\_1}$	$v_{we\_zi\_n_1\_1}$
		Zone Mean	$\dot{m}_{zm\_n_1\_1}$	$T_{zm\_n_1\_1}$	$c_{p\_zm\_n_1\_1}$	$w_{kg\_zm\_n_1\_1}$	$v_{we\_zm\_n_1\_1}$
		Zone Outlet	$\dot{m}_{zo\_n_1\_1}$	$T_{zo\_n_1\_1}$	$c_{p\_zo\_n_1\_1}$	$w_{kg\_zo\_n_1\_1}$	$v_{we\_zo\_n_1\_1}$
		Zone Exhaust	$\dot{m}_{zex\_n_1\_1}$	$T_{zex\_n_1\_1}$	$c_{p\_zex\_n_1\_1}$	$w_{kg\_zex\_n_1\_1}$	$v_{we\_zex\_n_1\_1}$
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
N	1	Zone Inlet	$\dot{m}_{zi\_1\_N}$	$T_{zi\_1\_N}$	$c_{p\_zi\_1\_N}$	$w_{kg\_zi\_1\_N}$	$v_{we\_zi\_1\_N}$
		Zone Mean	$\dot{m}_{zm\_1\_N}$	$T_{zm\_1\_N}$	$c_{p\_zm\_1\_N}$	$w_{kg\_zm\_1\_N}$	$v_{we\_zm\_1\_N}$
		Zone Outlet	$\dot{m}_{zo\_1\_N}$	$T_{zo\_1\_N}$	$c_{p\_zo\_1\_N}$	$w_{kg\_zo\_1\_N}$	$v_{we\_zo\_1\_N}$
		Zone Exhaust	$\dot{m}_{zex\_1\_N}$	$T_{zex\_1\_N}$	$c_{p\_zex\_1\_N}$	$w_{kg\_zex\_1\_N}$	$v_{we\_zex\_1\_N}$
	⋮	⋮	⋮	⋮	⋮	⋮	⋮
	n_N	Zone Inlet	$\dot{m}_{zi\_n_N\_N}$	$T_{zi\_n_N\_N}$	$c_{p\_zi\_n_N\_N}$	$w_{kg\_zi\_n_N\_N}$	$v_{we\_zi\_n_N\_N}$
		Zone Mean	$\dot{m}_{zm\_n_N\_N}$	$T_{zm\_n_N\_N}$	$c_{p\_zm\_n_N\_N}$	$w_{kg\_zm\_n_N\_N}$	$v_{we\_zm\_n_N\_N}$
		Zone Outlet	$\dot{m}_{zo\_n_N\_N}$	$T_{zo\_n_N\_N}$	$c_{p\_zo\_n_N\_N}$	$w_{kg\_zo\_n_N\_N}$	$v_{we\_zo\_n_N\_N}$
		Zone Exhaust	$\dot{m}_{zex\_n_N\_N}$	$T_{zex\_n_N\_N}$	$c_{p\_zex\_n_N\_N}$	$w_{kg\_zex\_n_N\_N}$	$v_{we\_zex\_n_N\_N}$

2.5. Data available directly from EnergyPlus

The labelling of system and zonal nodes described above varies across the different EnergyPlus building prototypes. As an example, Table 2-8 below summarizes the EnergyPlus variable names for the HVAC system and zone nodes of interest for the PSZ HVAC systems in the small office building prototype. The EnergyPlus variables names of these nodes in other building prototypes may be different, but the nodes are always present under. For each of the nodes listed in Table 2-8, EnergyPlus provides the associated air properties. The node air properties are in turn used to disaggregate the sensible and latent loads, as discussed in Section 3.

Table 2-8 Small Office HVAC System and Zone Nodes with EnergyPlus Variable Names

System or Zone	Node Information		
	Name	**Notation**	**EnergyPlus Variable Name**
System	Return Air	ra_x	SUPPLY EQUIPMENT INLET NODE
System	Outdoor Air	oa_x	OAINLET NODE
System	Relief Air	rfa_x	OARELIEF NODE
System	Mixed Air Inlet	ma_x	COOLCNODE (Draw-through); FANNODE (Blow-through)
System	Cooling Coil Inlet	cc_x	COOLCNODE
System	Heating Coil Inlet	hc_x	HEATCNODE
System	Supply Fan Inlet	sf_x	FANNODE
Supply	Supply Air	sa_x	SUPPLY EQUIPMENT OUTLET NODE
Zone	Zone Inlet	zi_z	DIRECT AIR INLET NODE
Zone	Zone	zm_z	ZONE MEAN
Zone	Zone Outlet	zo_z	RETURN AIR NODE
Zone	Zone Exhaust	zex_z	EXHASUT AIR NODE

3. *Thermodynamic Equations*

This section presents the thermodynamic equations used to calculate sensible and latent loads from the system and zone air properties presented in Section 2. As noted earlier, EnergyPlus generates system and zone air properties at nodes throughout the HVAC system as well as the zones served by the HVAC system. Using the equations and air property data our analysis separates the total space conditioning loads into four components: the latent and sensible loads, and the portion of each associated with outdoor air vs. the air recirculated from the conditioned space. Section 4 validates the calculations by comparing the calculated total latent and sensible space conditioning loads to those generated by EnergyPlus. The four component loads associated with the outdoor air and recirculated air cannot be validated as EnergyPlus does not disaggregate sensible and latent loads to this level.

3.1. Mass Balance

The sensible space-conditioning and latent cooling provided by an HVAC system can be disaggregated into the loads removed or provided from two air flows that circulate within the air loop for the system; the recirculated return air flow and the outdoor air flow. The net mass flow rate around the system is constant, so air entering from outside is always balanced by exhausting part of the return air through the system relief outlet node. This is in addition to any air exhausted directly through zone exhaust nodes.

The total flow of air from the zones back to the system is called the return air: for HVAC system, x, the relationship between return air, zone air, and exhaust air is represented by the following expression:

$$\dot{m}_{ra\_x} = \sum_{z=1}^{n_x} \dot{m}_{zi\_z\_x} - \sum_{z=1}^{n_x} \dot{m}_{zex\_z\_x} = \sum_{z=1}^{n_x} \dot{m}_{zo\_z\_x}, \quad (1)$$

where:

$\sum_{z=1}^{n_x} \dot{m}_{zi\_z\_x}$ = sum of inlet zone mass flow rates served by HVAC system, *x*,
$\sum_{z=1}^{n_x} \dot{m}_{zex\_z\_x}$ = sum of zone mass flow rates exhausted from the zones served by HVAC system *x*, and
$\sum_{z=1}^{n_x} \dot{m}_{zo\_z\_x}$ = sum of outlet mass flow rates from the zones served by HVAC system *x*.

The relief air is the amount of return air exhausted in order to keep the mass flow rate constant when outdoor air is drawn into the HVAC system. The outdoor air mass flow rate drawn into the HVAC system is equal to the mass flow rate of the relief air plus the sum of the zone mass flow rates that have been exhausted, as shown by the following expression:

$$\dot{m}_{oa\_x} = \dot{m}_{rfa\_x} + \sum_{z=1}^{n_x} \dot{m}_{zex\_z\_x}, \quad (2)$$

The recirculated air is defined as the portion of return air flow rate that is not exhausted:

$$\dot{m}_{rcrc\_x} = \dot{m}_{ra\_x} - \dot{m}_{rfa\_x}, \quad (3)$$

where:

$\dot{m}_{rcrc\_sysx}$ = return air mass flow rate recirculated to the HVAC system, *x*.

The mixed air flow rate is equal to the sum of the recirculated air flow rate and the outdoor air flow rate:

$$\dot{m}_{ma\_x} = \dot{m}_{rcrc\_x} + \dot{m}_{oa\_sx}. \quad (4)$$

The mixed air flow rate is also equal to the HVAC system's supply air flow rate;

$$\dot{m}_{sa\_x} = \dot{m}_{ma\_x}. \quad (5)$$

For HVAC system, *x*, the supply air mass flow rate equals the sum of the mass flow rates into each zone:

$$\dot{m}_{sa\_x} = \sum_{z=1}^{n_x} \dot{m}_{zi\_z\_x}. \quad (6)$$

The zone air mass flow rate represents both airflow into and out of the zone, including infiltration, which is generally small. The sum of the mass flow rates delivered to all zones within the building defines the total mass flow rate of the building, $\dot{m}_{bldg}$:

$$\dot{m}_{bldg} = \sum_{x=1}^{N} \dot{m}_{sa\_x}. \quad (7)$$

3.2. *Energy Balance*

Section 3.2 explains how the sensible and latent components of the space cooling and heating loads are calculated. EnergyPlus uses weather data along with building characteristics to calculate the heat generated at a specific time-step, and then calculates the rate of cooling or heating required by the HVAC system to maintain the zonal set-point temperatures (DOE-EERE 2018). In this report, the total cooling or heating rate of the HVAC system is disaggregated into the ventilation load and the zonal load, and then further disaggregated into sensible and latent components based on air properties at different points throughout the HVAC system. The air properties used in the load calculations are temperature, humidity ratio, mass flow rate, specific heat, and latent heat of vaporization.

The ventilation load is calculated using the ventilation rate for each prototype building and the air properties of the outdoor air and the supply air for a specific time-step. The zonal loads are calculated using the change in air properties between the zone inlet node (where air enters a zone) and the zone outlet node (where air is either exhausted to the outdoors or returned to the HVAC system) for a time-step. The zone loads represent the amount of cooling or heating required to offset the internal gains or losses in each zone. Internal loads represent the loads from people, lighting, equipment, infiltration, windows, and walls.

3.2.1. Sensible heat balance

System sensible load

Within HVAC system *x*, the rate of sensible load removed or provided between a node upstream of the supply air node and the supply air node is determined with the following expression:

$$h_{s\_j\_x} = \bar{c}_{p\_j\_x} \times \dot{m}_{j\_x} \times (T_{j\_x} - T_{sa\_x}), \quad (8)$$

where,

$h_{s\_j\_x}$ = rate of sensible load removed or provided by HVAC system, *x*, between the upstream and supply air nodes (kW),
$\bar{c}_{p\_j\_x}$ = mean value of the specific heat between the upstream and supply air nodes (kJ/kg-°C),
$\dot{m}_{j\_x}$ = mass flow rate at supply air node (kg/s), and
T_{j_x} = dry-bulb air temperature at the upstream node (°C), and
T_{sa_x} = dry-bulb air temperature at the supply air node (°C).

The rate of sensible load calculated in equation 8 represents the total sensible load and includes both the effects of recirculated return air and the outdoor air. Outdoor air drawn into the system is used to meet code-related ventilation requirements which are typically based on building occupancy. For HVAC systems equipped with economizers, additional outdoor air is drawn into the HVAC system at times when the outdoor air conditions are suitable for space-cooling and can displace the need for mechanical cooling.

At outdoor air conditions when mechanical cooling is needed, the HVAC system must condition the outdoor air to remove the sensible and latent load. When mechanical heating is needed, the HVAC system conditions the outdoor air to add sensible load. In developing energy balance equations around the air loop, the heat rejected from the supply fan must also be accounted for as part of the sensible load. For draw-through HVAC systems, the fan's effect on the air properties (e.g., to increase the dry-bulb temperature) is captured in equation 8 above as the supply air node is after the supply fan. For blow-through systems, assuming the upstream node is before the fan, equation 8 also captures the fan's effect on the air properties.

The rate of sensible load removed or provided by HVAC system *x* to the outdoor air flow, in order to bring its air properties to supply air conditions, is expressed as:

$$h_{s\_oa\_x} = \bar{c}_{p\_oa\_x} \times \dot{m}_{oa\_x} \times (T_{oa\_x} - T_{sa\_sx}), \qquad (9)$$

where,

$h_{s\_oa\_x}$ = rate of sensible load removed or provided to the outdoor air flow (kW), and
$\bar{c}_{p\_oa\_x}$ = mean value of the specific heat between the outdoor air and supply air nodes (kJ/kg-°C).

The rate of sensible load removed or provided by HVAC system *x* to the recirculated return air flow, in order to bring its air properties to supply air conditions is expressed as follows:

$$h_{s\_rcrc\_x} = \bar{c}_{p\_rcrc\_x} \times \dot{m}_{rcrc\_x} \times (T_{rcrc\_x} - T_{sa\_sx}), \qquad (10)$$

where,

$h_{s\_rcrc\_x}$ = rate of sensible load removed or provided to the recirculated air (kW), and
$\bar{c}_{p\_rcrc\_x}$ = mean value of the specific heat between the recirculated return air and supply air nodes (kJ/kg-°C).

The outdoor and recirculated air flows are combined into a single stream, with air properties denoted as the mixed node *ma_x*. The rate of sensible load removed or provided by HVAC system *x* to the mixed air flow is:

$$h_{s\_ma\_x} = \bar{c}_{p\_ma\_x} \times \dot{m}_{ma\_x} \times (T_{ma\_x} - T_{sa\_sx}), \qquad (11)$$

where,

$h_{s\_ma\_x}$ = rate of sensible load removed or provided by HVAC system, *x*, in order to bring mixed air properties to supply air conditions (kW), and
$\bar{c}_{p\_ma\_x}$ = mean value of the specific heat between the mixed air and supply air nodes (kJ/kg-°C).

Because the mixed air flow is the combination of the recirculated return air flow rate and the outdoor air flow rate, the sensible load due to the mixed air flow rate is equal to the sum of the loads attributed to each air stream:

$$h_{s\_ma\_x} = h_{s\_rcrc\_x} + h_{s\_oa\_x}. \tag{12}$$

The supply air from HVAC system, *x*, is used to condition one or more zones, *z*. Some types of HVAC systems (e.g., variable air volume) utilize reheat coils for each zone to raise the dry bulb air temperature of the supply air, if needed, to meet each zone's set point temperature. The rate of sensible load provided between supply air node and each of the zone inlet nodes is:

$$h_{s\_rh\_x} = \sum_{z=1}^{n_x} (\bar{c}_{p\_k\_rhz\_x} \times \dot{m}_{zi\_z\_x} \times (T_{sa\_x} - T_{zi\_z\_x})), \tag{13}$$

where,

$h_{s\_rh\_x}$ = rate of sensible load provided from the reheat coils to all zones conditioned by HVAC system *x* (kW), and
$\bar{c}_{p\_k\_rh\_x}$ = mean value of the specific heat between the supply air and the zone inlet air nodes for each zone (kJ/kg-°C).

The system load removed or provided by HVAC system *x*, and all reheat coils that are utilized to provide additional sensible load is determined with the following expression:

$$h_{s\_x} = h_{s\_ma\_x} + h_{s\_rh\_x} = h_{s\_rcrc\_x} + h_{s\_oa\_x} + h_{s\_rh\_x}. \tag{14}$$

where,

h_{s_x} = rate of total sensible load removed or provided by HVAC system, *x*, and all reheat coils serving zones that are space conditioned by HVAC system, *x* (kW).

Zone sensible load

The zonal load associated with the internal gains from people, plug loads, lighting, and other miscellaneous loads, is determined by the following expression:

$$h_{s\_z\_x} = \sum_{z=1}^{n_x} (\bar{c}_{p\_k\_z\_x} \times \dot{m}_{zi\_z\_x} \times (T_{zo\_z\_x} - T_{zi\_z\_x})), \tag{15}$$

where,

$h_{s\_z\_x}$ = rate of sensible load removed or provided for all zones served by HVAC system *x* (kW), and
$\bar{c}_{p\_k\_z\_x}$ = mean value of the specific heat between the zone inlet air and zone outlet air nodes for each zone (kJ/kg-°C).

Some of the sensible load removed or provided for all the zones may be directly exhausted from the zone. The exhausted air carries away part of the sensible load that would otherwise have been put on the HVAC system. The sensible load associated with the zone exhaust air is:

$$h_{s\_zex\_x} = \sum_{z=1}^{n_x} (\bar{c}_{p\_k\_z\_x} \times \dot{m}_{zex\_z\_x} \times (T_{zo\_z\_x} - T_{zi\_z\_x})), \tag{16}$$

where,

$h_{s\_zex\_x}$ = rate of sensible load exhausted from zone z (kW).

The net zonal loads plus the load introduced by outdoor air, add up to the total sensible load on the system; hence:

$$h_{s\_x} = (h_{s\_z\_x} - h_{s\_zex\_x}) + h_{s\_oa\_x} + h_{s\_rhz\_x}. \tag{17}$$

As noted above, the sensible load removed or provided by HVAC system, x, and all reheat coils can also be expressed as:

$$h_{s\_x} = h_{s\_rcrc\_x} + h_{s\_oa\_x} + h_{s\_rhz\_x}, \tag{18}$$

with the sensible load in recirculated air flow equal to

$$h_{s\_rcrc\_x} = h_{s\_z\_x} - h_{s\_zex\_x}. \tag{19}$$

3.2.2. Latent heat balance

System latent load

Within HVAC system x, the rate of latent cooling load removed between a node upstream of the supply air node and the supply air node is determined with the following expression:

$$h_{l\_j\_x} = \dot{m}_{j\_x} \times v_{we\_j\_x} \times (w_{kg\_j\_x} - w_{kg\_sa\_x}), \tag{20}$$

where,

$h_{l\_j\_x}$ = rate of latent cooling load removed by HVAC system, x, between the upstream and supply air nodes (kW),
$\dot{m}_{j\_x}$ = mass flow rate between the upstream and supply air nodes (kg/s),
$v_{we\_j\_x}$ = latent heat of vaporization for the upstream node (kJ/kg) as calculated with the following expression $= 2500.9 + 1.85895 \times T_{j\_x}$, and
$w_{kg\_j\_x}$ = humidity ratio at the upstream air node ($kg_{water}/kg_{dry\ air}$).

Following the same procedure used for the sensible loads, latent loads can be disaggregated into those associated with the recirculated and the outdoor air flows. The equations below summarize the various components of latent load.

The latent cooling load removed from the outdoor air stream is:

$$h_{l\_oa\_x} = \dot{m}_{oa\_x} \times v_{we\_oa\_x} \times (w_{kg\_oa\_x} - w_{kg\_sa\_x}). \tag{21}$$

where,

$h_{l\_oa\_x}$ = rate of latent cooling load removed by HVAC system, *x*, in order to bring outside air properties to supply air conditions (kW), and
$v_{we\_oa\_x}$ = latent heat of vaporization at the outdoor air node (kJ/kg).

The latent cooling load removed from the recirculated return air flow is:

$$h_{l\_rcrc\_x} = \dot{m}_{rcrc\_x} \times v_{we\_rcrc\_x} \times (w_{kg\_rcrc\_x} - w_{kg\_sa\_x}), \tag{22}$$

where,

$h_{l\_rcrc\_x}$ = rate of latent cooling load removed by HVAC system, *x*, in order to bring recirculated return air properties to supply air conditions (kW), and
$v_{we\_rcrc\_x}$ = latent heat of vaporization at the recirculated return air node (kJ/kg).

The total latent cooling rate, which is identical to the load removed between the mixed and supply air nodes is:

$$h_{l\_x} = h_{l\_ma\_x} = \dot{m}_{ma\_x} \times v_{we\_ma\_x} \times (w_{kg\_ma\_x} - w_{kg\_sa\_x}), \tag{23}$$

where,

$h_{l\_ma\_x}$ = rate of latent cooling load removed by HVAC system, *x*, in order to bring mixed air properties to supply air conditions (kW), and
$v_{we\_ma\_x}$ = latent heat of vaporization between at the mixed air node (kJ/kg), and
h_{l_x} = rate of total latent load removed by HVAC system, *x* (kW).

The total latent load is the sum of the outdoor and recirculated components:

$$h_{l\_x} = h_{l\_rcrc\_x} + h_{l\_oa\_x}. \tag{24}$$

Zone latent load

The zonal latent load associated with the internal gains from people, infiltration etc. is:

$$h_{l\_z\_x} = \sum_{z=1}^{n_x} (\dot{m}_{zi\_z\_x} \times v_{we\_zi\_z\_x} \times (w_{kg\_zo\_z\_x} - w_{kg\_zi\_z\_x})), \tag{25}$$

where,

$h_{l\_z\_x}$ = rate of latent cooling load removed from all zones, which HVAC system, *x*, is serving (kW).

If air is exhausted directly from the zone, the latent load removed is:

$$h_{l\_zex\_x} = \sum_{z=1}^{n_x}(\dot{m}_{zex\_z\_x} \times v_{we\_zi\_z\_x} \times (w_{kg\_zo\_z\_x} - w_{kg\_zi\_z\_x})), \tag{26}$$

where,

$h_{l\_zex\_x}$ = rate of latent load removed from all zones that is exhausted as exhaust air (kW).

The total latent load on HVAC system *x* is:

$$h_{l\_x} = (h_{l\_z\_x} - h_{l\_zex\_x}) + h_{l\_oa\_x}. \tag{27}$$

As noted above, the latent load removed by HVAC system, *x*, can also be expressed as:

$$h_{l\_x} = h_{l\_ma\_x} = h_{l\_rcrc\_x} + h_{l\_oa\_x}, \tag{28}$$

with the latent load in recirculated air flow equal to

$$h_{l\_rcrc\_x} = h_{l\_z\_x} - h_{l\_zex\_x}. \tag{29}$$

4. Validation of Calculation Methods

In this analysis, thermodynamic relations presented in Section 3, along with the air properties output by EnergyPlus, are used to calculate the disaggregated latent and sensible loads for the outdoor and recirculated air streams. The loads are calculated as loads on the individual HVAC systems. The various individual loads that occur in each zone, due to people, envelope gains, and equipment are captured in the HVAC system load associated with the recirculated air. This section also describes the methods used to validate the thermodynamic calculations. This validation step is used to confirm that the division of sensible and cooling loads into contributions from the recirculated and outdoor air streams provides correct estimates of these separate loads.

EnergyPlus directly reports the heating and cooling rates for the system coils, as summarized in Table 4-1. This table summarizes the variable names, notation, and equation numbers for the loads presented in Section 3, and the corresponding EnergyPlus variable names, if they exist. The methods are tested by comparing the loads calculated from air conditions, for each system, with the coil rates output by EnergyPlus directly. In the diagnostics, data output at both a 10-minute and a 1-hour time step are used. The actual time step used in EnergyPlus is much shorter, and adapts to the details of load balance. Hence, the output data represent averages over the output time step.

In order for the results to match the EnergyPlus output, two adjustments are necessary. As noted above, for draw-through systems the supply fan node is after the heating and cooling coil nodes; hence, to match the calculations to the reported heating and cooling coil rates a correction must be made for the fan heat energy (which is always included in the calculations in this analysis). The other adjustment is to account for the fact that during hours of low load the system may cycle on and off, which is not always reflected in the EnergyPlus cooling coil rates. The equations presented in Section 3 are valid for any time step, as long as the physical quantities are interpreted correctly. At the hourly time step, the data should be interpreted as averages over the hour, with any period of the time where the system cycles to the off state included in the average. For the EnergyPlus output, while the mass flow and fan heat output are true averages in this sense, the sensible and latent cooling rates reported for some systems are the rates calculated only for the time when the system is running. Hence, to match the true hourly average, these rates need to be adjusted for the cycling ratio, f_{cyc}, which this analysis defines as the fraction of the output time step that the system is on.

Table 4-1 HVAC System and Zone Loads reported by EnergyPlus

System or Zone	Variable Name	Variable Notation	Eqn. No.	EnergyPlus Variable Name(s)
System	Sensible Cooling Load	h_{s_x}	(11), (12), (13)	COOLING COIL SENSIBLE COOLING RATE minus FAN ELECTRIC RATE for draw-through systems (when h_{s_x} > 0)
	Sensible Heating Load			HEATING COIL AIR HEATING RATE plus FAN ELECTRIC RATE for draw-through systems (when h_{s_x} < 0)
	Latent Cooling Load	h_{l_x}	(24), (25), (26)	COOLING COIL LATENT COOLING RATE
Reheat	Sensible Heating Load	$h_{s\_rhz\_x}$	(14)	VAV BOX REHEAT COIL HEATING COIL HEATING RATE
Zone	Sensible Cooling Load	$h_{s\_z\_x}$	(16)	ZONE AIR SYSTEM SENSIBLE COOLING RATE (when $h_{s\_z\_x}$ > 0)
	Sensible Heating Load			ZONE AIR SYSTEM HEATING RATE (when $h_{s\_z\_x}$ < 0)
	Latent Cooling Load	$h_{l\_z\_x}$	(27)	Not available

For Unitary Split Systems, used in the Mid-rise Apartment prototypes, no adjustment is necessary. For PTACS and DOAS systems, only the fan heat adjustment is needed. For the other systems, the reported fan energy is used to calculate the cycling ratio, with the method depending on whether the system is single- or variable-speed. For single-speed systems (PSZ and MS_CAV), the cycling ratio for a given period is equal to the ratio of the fan energy in that period to the reported maximum fan energy over all periods; the latter corresponds to periods when the system doesn't cycle. For variable speed systems (MS_VAV and Fan Coil) the method is more complicated, as these systems can reduce the mass flow to a minimum value before they begin cycling. This behavior is illustrated in Figure 4-1, which shows a scatter plot of the fan energy vs. the mass flow rate, for a VAV system in the Medium Office-New prototype. As demand for cooling decreases, the mass flow and fan energy decrease, but eventually reach a minimum value (represented by the red circle in Figure 4-1), below which the system starts to cycle. It is confirmed that the system is cycling in these low mass flow hours because the relationship between mass flow and fan energy becomes linear. Hence, cycling occurs only in those hours in which the mass flow/fan energy are below the system minimum, and during these hours the cycling ratio is equal to the fan energy for the hour divided by the system minimum value.

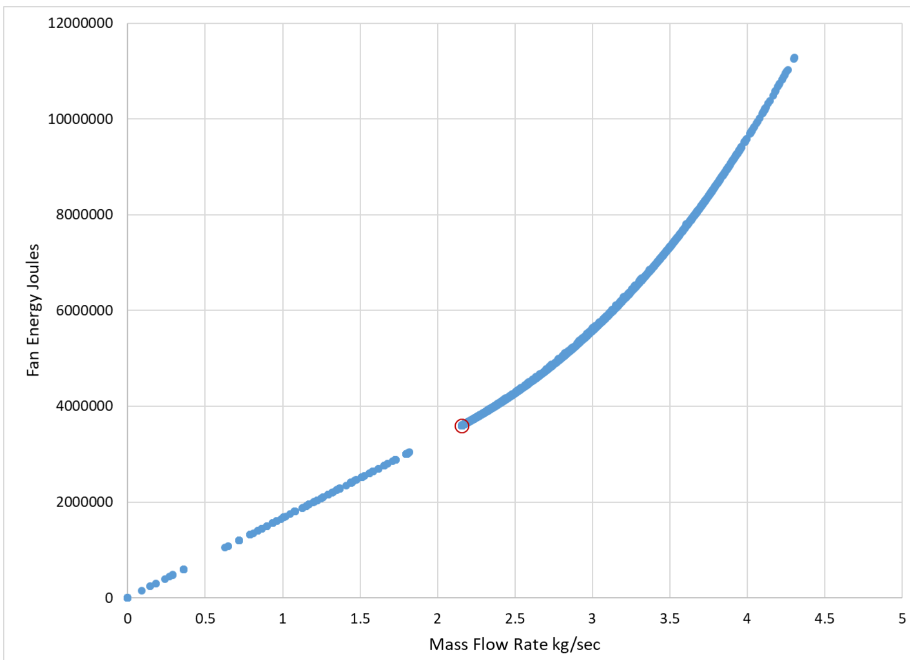


Figure 4-1 Relationship between Fan Energy and Mass Flow Rate for Variable Air Volume HVAC System in Medium Office Building

For both fixed and variable speed systems, to correct for cycling, the EnergyPlus reported sensible and latent cooling coil rates were multiplied by the cycling ratio and the resulting values were compared to our calculations based on air conditions. A summary of this validation check is presented in Figure 4-2. This figure shows a scatter plot of annual values of the latent and sensible loads reported by EnergyPlus (with the adjustments described above) *vs*. those calculated from the air conditions. The data are for all the systems and buildings in Atlanta, with the sensible loads shown as solid blue dots and the latent loads as open red squares. The axes are logarithmic to accommodate the wide range of system sizes. Almost all systems have a discrepancy of less than a fraction of a percent. Out of a total of 442 systems in the database there are five that show large discrepancies between the calculated and reported loads. All the errors arise for CAV systems, in Pre-1980 vintage Secondary School and Large Hotel. By comparing the CAV system data to the data for the VAV systems that serve the same zones in the Post-1980 and New vintages, it is surmised that the loads calculated from air conditions are correct and there is a problem with the EnergyPlus reported coil rates.

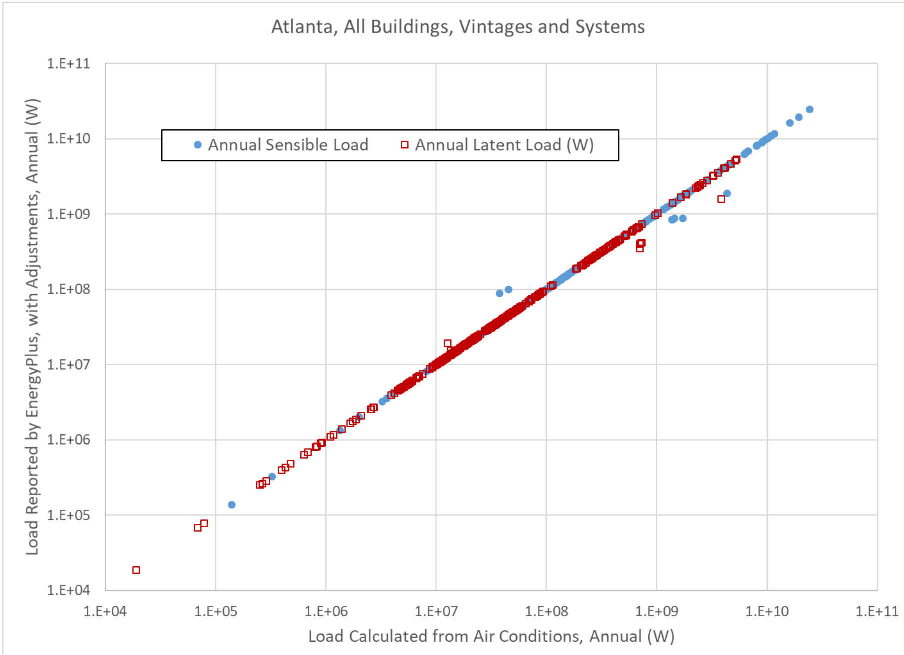


Figure 4-2 Validation Check Summary for Atlanta Systems

5. Results

The full simulation database consists of 10-minute time-step data, for a full year, for the 16 building types, 3 vintages and 18 climate zones. Within the 16 building types, there are several hundred individual systems for which the nodal data are collected. To convert these to a comprehensible summary form, two processing steps are used and described below.

The first step is to provide some normalization so that loads can be compared across systems of different sizes. The HVAC sizing is part of the building prototype definition, and capacities vary from about 2,000 Btu/hr for the smallest PSZ cooling coils to a few million BTU/hr for the largest VAV systems. To facilitate comparison between systems, the data are normalized to represent quantities per-square-foot of conditioned space. The area of conditioned space assigned to a system is defined as the area of all zones served by that system. The average capacity per square foot by building type for three climate zones is shown in

Table 5-1. The data are for cooling system capacity, heating system capacity, and reheat coil capacity, summed over all systems in a building. The table shows the New and Pre-1980 vintages for comparison (zone areas do not change as a function of vintage). The system types in the building are indicated in parentheses below the building type. The colored bars in the table are another indication of magnitude. Even after normalization to per-square-foot there is considerable variation in the capacities by building type and vintage. In general, for newer vintages, the building envelope improvements allow systems to be down-sized by up to a factor of two. Heating capacities are more sensitive to climate than cooling capacities. The buildings with high occupancy (hotels, apartment, schools) have the largest capacity per-square-foot.

The second processing step is to use time-averaging to convert the ten-minute time series data to a more compact representation of load shapes. To accomplish this, hourly load profiles by month and day-type were constructed. The day-types are defined as weekday and weekend. These profiles are calculated by averaging the load in a given month and hour over all the days of that day-type.

Normalization and time-averaging are applied to each of the four component loads, for each building and vintage, in all of the climate zones. In the figures of this section the load results are illustrated for a few selected building types (Medium Office, Stand-alone Retail, and Secondary School, new vintage), in three climates. The plots use Phoenix, Houston and Chicago as representative of hot-dry, hot-humid and cold climates. The full database contains all buildings, vintages and climate zones.

Figure 5-1 shows hourly, weekday cooling load profiles for April and August, decomposed into the latent/sensible and ventilation/recirculated components. The figure shows two new construction building types: Medium Office on the left (which uses a VAV system), and Stand-alone Retail on the right (single speed PSZ systems), in the three climate locations. In these plots, the ventilation loads are shown in green, and the recirculated loads in blue. The sensible contribution is plotted using solid bars, and the latent contribution is shown with open bars. On the horizontal axis, for each hour, the data for March and August are shown side-by-side. The vertical scale in each plot is the same. From the figure, it is clear that the ventilation component of latent loads is dominant in all climates, particularly for the Stand-alone Retail building. In the hot-humid climate (Houston), ventilation sensible and latent loads are approximately equal. In the hot-humid and hot-dry climates, shoulder season cooling (April) is dominated by the recirculated sensible cooling loads, presumably from envelope gains. Figure 5-2 shows the same weekday cooling load profiles but for the post-1980 construction building types. As evidenced by Figure 5-2, the overall cooling load in each building type is greater due to less restrictive energy code requirements which the buildings had to comply with.

Table 5-1 Average Cooling Capacity per Square Foot by Building Type and Climate Zone

Capacity BTu/hr/SqFt		New Buidlings			Pre-1980 Buildings		
	City	Cooling	Heating	Reheat	Cooling	Heating	Reheat
FULLSERVICERESTAURANT	CHICAGO-OHARE	105	293		131	338	
(PSZ)	HOUSTON	107	213		141	255	
	PHOENIX	105	177		148	227	
LARGEHOTEL	CHICAGO-OHARE	523	416	12	596	489	28
(DOAS, Fan Coil, VAV)	HOUSTON	510	377	11	703	415	21
	PHOENIX	543	334	10	748	361	17
LARGEOFFICE	CHICAGO-OHARE	119	23	41	136	23	57
(VAV)	HOUSTON	122	12	36	156	11	46
	PHOENIX	122	7	31	155	5	39
MIDRISEAPARTMENT	CHICAGO-OHARE	385	517		924	1035	
(Split System)	HOUSTON	352	319		648	620	
	PHOENIX	378	243		714	464	
OUTPATIENT	CHICAGO-OHARE	95	15	53	111	13	74
(VAV)	HOUSTON	99	4	45	123	5	61
	PHOENIX	100	3	43	126	3	58
PRIMARYSCHOOL	CHICAGO-OHARE	199	343	64	233	364	95
(CAV/VAV, PSZ)	HOUSTON	215	251	51	311	299	90
	PHOENIX	215	207	44	321	250	76
SECONDARYSCHOOL	CHICAGO-OHARE	350	730	56	349	760	125
(CAV/VAV, PSZ)	HOUSTON	361	525	46	414	558	83
	PHOENIX	360	441	38	430	464	67
SMALLHOTEL	CHICAGO-OHARE	1046	1310		1250	1637	
(PTACS, PSZ)	HOUSTON	1138	980		1372	1013	
	PHOENIX	1149	820		1436	766	
SMALLOFFICE	CHICAGO-OHARE	116	183		249	319	
(PSZ)	HOUSTON	128	176		258	325	
	PHOENIX	131	172		258	329	
STRIPMALL	CHICAGO-OHARE	255	406		531	716	
(PSZ)	HOUSTON	292	248		543	402	
	PHOENIX	283	208		536	305	
SUPERMARKET	CHICAGO-OHARE	311	558		466	711	
(PSZ)	HOUSTON	282	436		362	510	
	PHOENIX	268	382		331	440	
WAREHOUSE	CHICAGO-OHARE	61	93		116	164	
(CAV)	HOUSTON	49	62		73	93	
	PHOENIX	49	48		68	66	

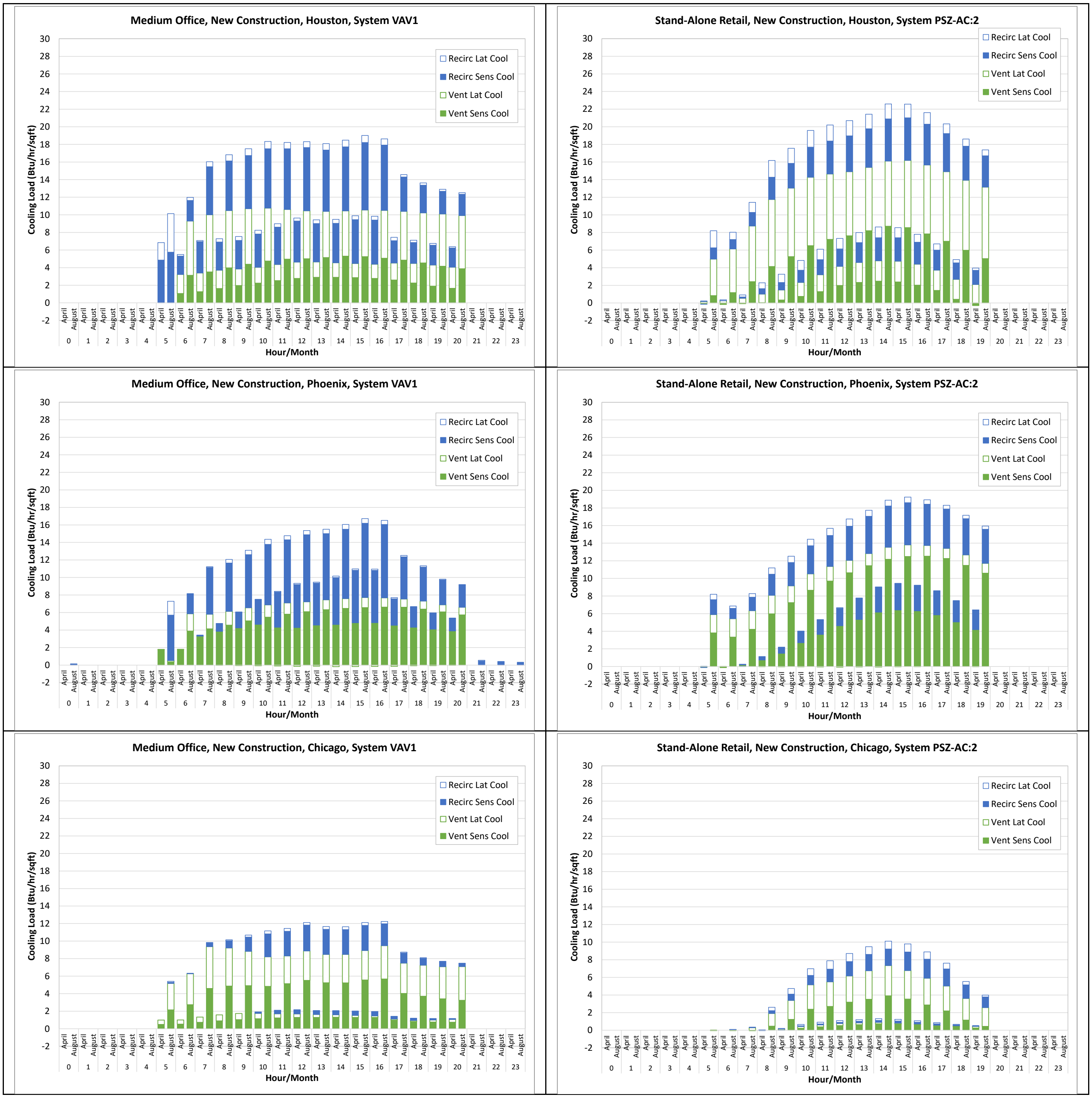


Figure 5-1 Weekday Cooling Load Profiles: New Construction Medium Office and Stand-Along Retail, Houston, Phoenix, and Chicago Climates

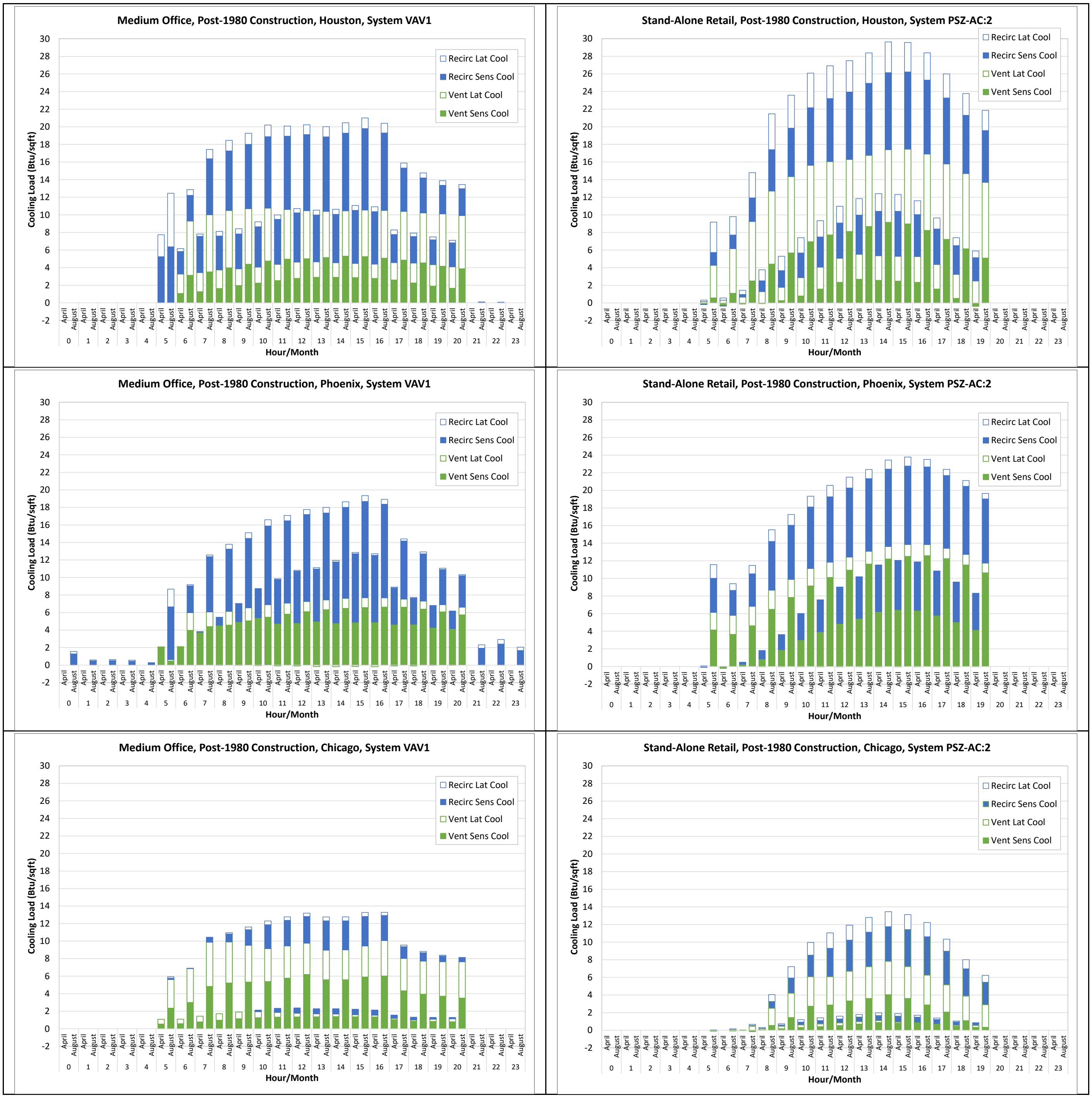


Figure 5-2 Weekday Cooling Load Profiles: Post-1980 Construction Medium Office and Stand-Alone Retail, Houston, Phoenix, and Chicago Climates

Monthly variation in loads is illustrated in Figure 5-3. The plot shows the new construction Medium Office on the left, and the new construction Secondary School on the right. In this plot, the hourly data are summed to provide a single value for each month and day-type. This metric is comparable to a typical daily load. The loads are again divided into latent/sensible and ventilation/recirculated, with heating loads included in orange. The heating load on the system coil is separate from the heating provided by reheat coils, as these two types of system can potentially be operated differently. In the CRB prototypes, reheat is only used for multi-zone HVAC systems, to ensure that zones with different loads can maintain the building set-point temperature. In heating season, the reheat coils are used if a zone requires more heat than the supply air temperature that is provided by the heating coil. During cooling season, the reheat coils are used to increase the supply air temperature if a zone requires less cooling, or in some cases, requires heating while another zone requires cooling. Our review of the EnergyPlus output for the CRB buildings indicates that there is no significant reheat during the summer cooling season (May-September), as can be seen in Figure 5-3. Reheat for humidity control is only used in certain zones of the hospital and outpatient healthcare buildings. Reheat was not used for humidity control in any other building. The figure shows that the Secondary School loads are generally higher, due to higher occupancy. Because of the corresponding higher ventilation requirement, these loads are again dominated by the ventilation component. The ventilation air stream includes the use of economizers, which are used only in dryer climates. As noted previously in Table 2-5, economizers are not used in climate zones that are humid and warm (i.e., southeastern portion of the U.S.). Economizers are primarily used in shoulder months (i.e., not in the summer and winter months) and tend to reduce sensible loads but could increase latent loads if the outdoor air is humid.

Figure 5-4 provides another view of the relative size of latent and sensible loads, showing three building types (Medium Office, Stand-alone Retail and Secondary School, all New vintage), and two climates. The percent of total load that is sensible/latent are plotted on the vertical/horizontal axes, with solid markers for March and open markers for August. Each point represents one system in the building. In Phoenix, latent loads never exceed 20%, while for Houston they can approach 60% of total load. The variation in the percent of latent vs. sensible can vary significantly for different systems within a single building, for example for Stand-alone Retail, depending on whether the system provides ventilation air.

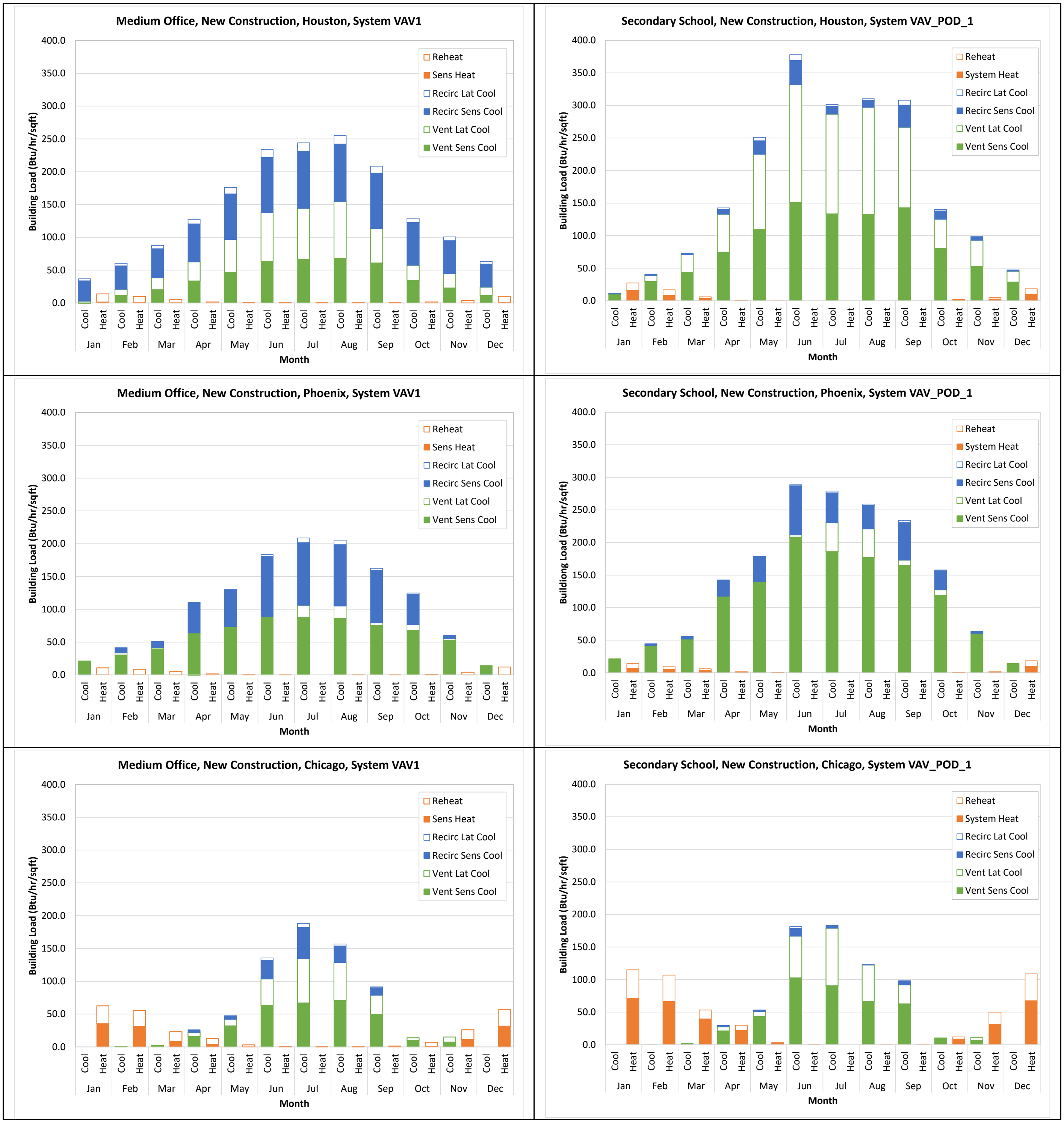


Figure 5-3 Monthly Building Load Profiles: New Construction Medium Office and Secondary School, Houston, Phoenix, and Chicago Climates

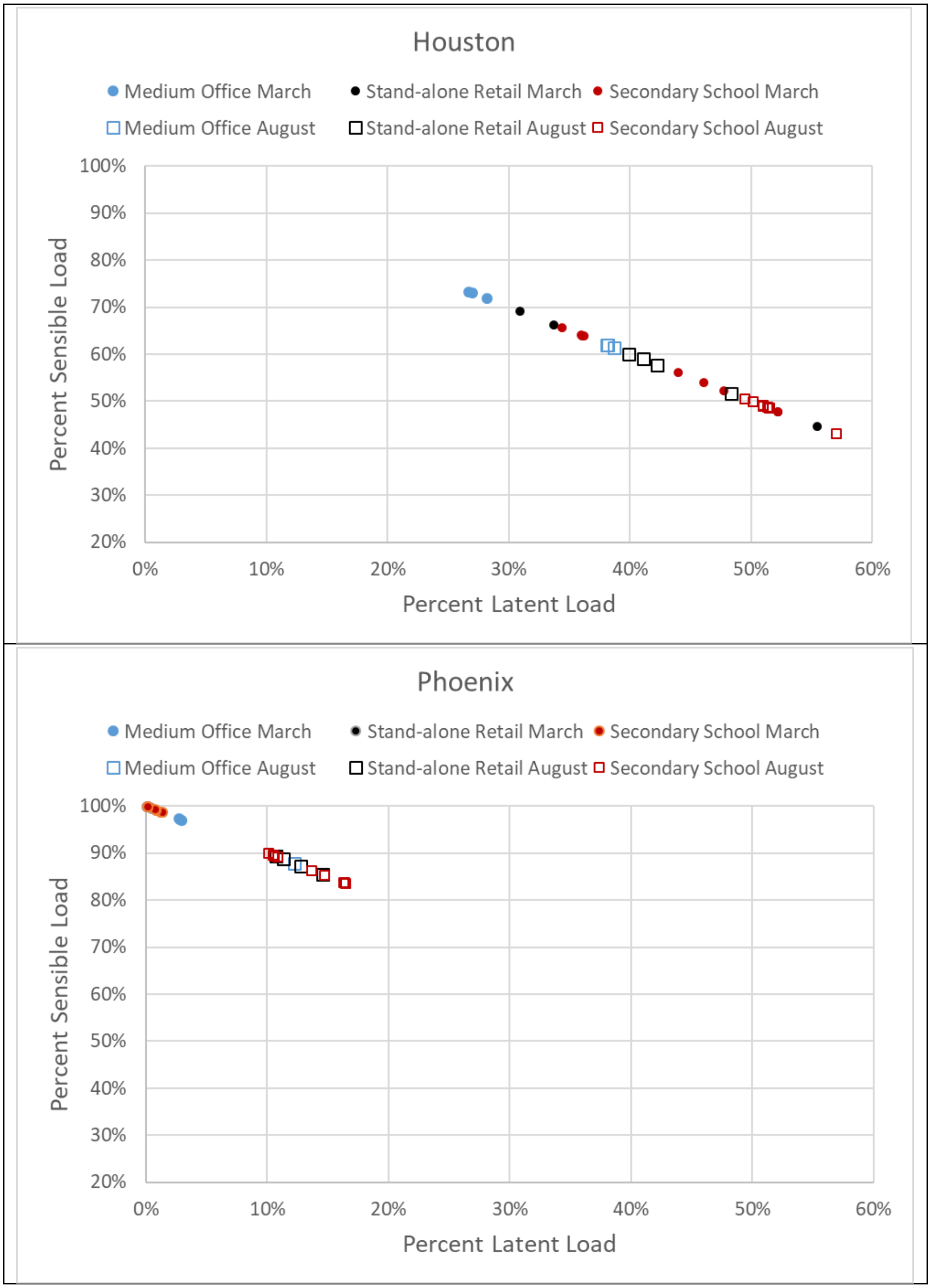


Figure 5-4 Sensible vs. Latent Loads in Houston and Phoenix

Figure 5-5 presents more detail on latent loads and humidity conditions. The figures on the left side of the grid provide a sense of how the operation of the ventilation system correlates with latent loads. These figures show, for Medium Office-New in the three climate zones, the ventilation and recirculated latent loads plotted as bars (left axis), and two ratios plotted as lines (right axis). The two ratios are the percent of mass flow around the air loop that is made up by outdoor air (light grey), and the ratio of sensible to total load (sensible heat ratio or SHR, black line). On the horizontal axis is the hour of day and the month, with overnight hours excluded. The axes are the same for all plots. As expected, in all climates the SHR is anti-correlated with the percent of outdoor air. The plot for Houston shows a pattern of high ventilation in evening hours, which then drops rapidly as the system operation is reduced overnight. High ventilation causes the latent loads to spike. In Phoenix ventilation is reduced mid-day during hot months. Both Phoenix and Chicago use an economizer to provide cooling during shoulder months, if the outdoor air temperature is below the return air temperature. The ventilation rate and minimum outdoor airflow schedule does not change by climate zone (DOE-EERE 2020b).

The plots on the right-hand side of Figure 5-5 show scatter plots of the supply-node humidity ratio (y-axis) vs. the outdoor air humidity ratio (x-axis). The weekday hours are plotted, divided into two groups: 6a.m. to 8 p.m., when buildings can be expected to be occupied (blue markers), and the rest of the hours, during which time the building is likely to be unoccupied (red markers). In this plot, for each climate, data for all the VAV systems across all buildings that have VAV systems are included in the plot. The rationale is that the operation of a VAV system during occupied hours should not be dependent on the building type. Overall this plot shows that, during occupied hours, the supply-node humidity level is correlated with outdoor humidity up to a point where it levels off at a value determined by the cooling coil conditions, approximately 0.008. During off-hours, introduction of ventilation air without additional conditioning causes supply-node conditions to rise significantly in Chicago and Houston, but not in the relatively dry climate of Phoenix. Note that supply-node conditions are not identical to zone conditions.

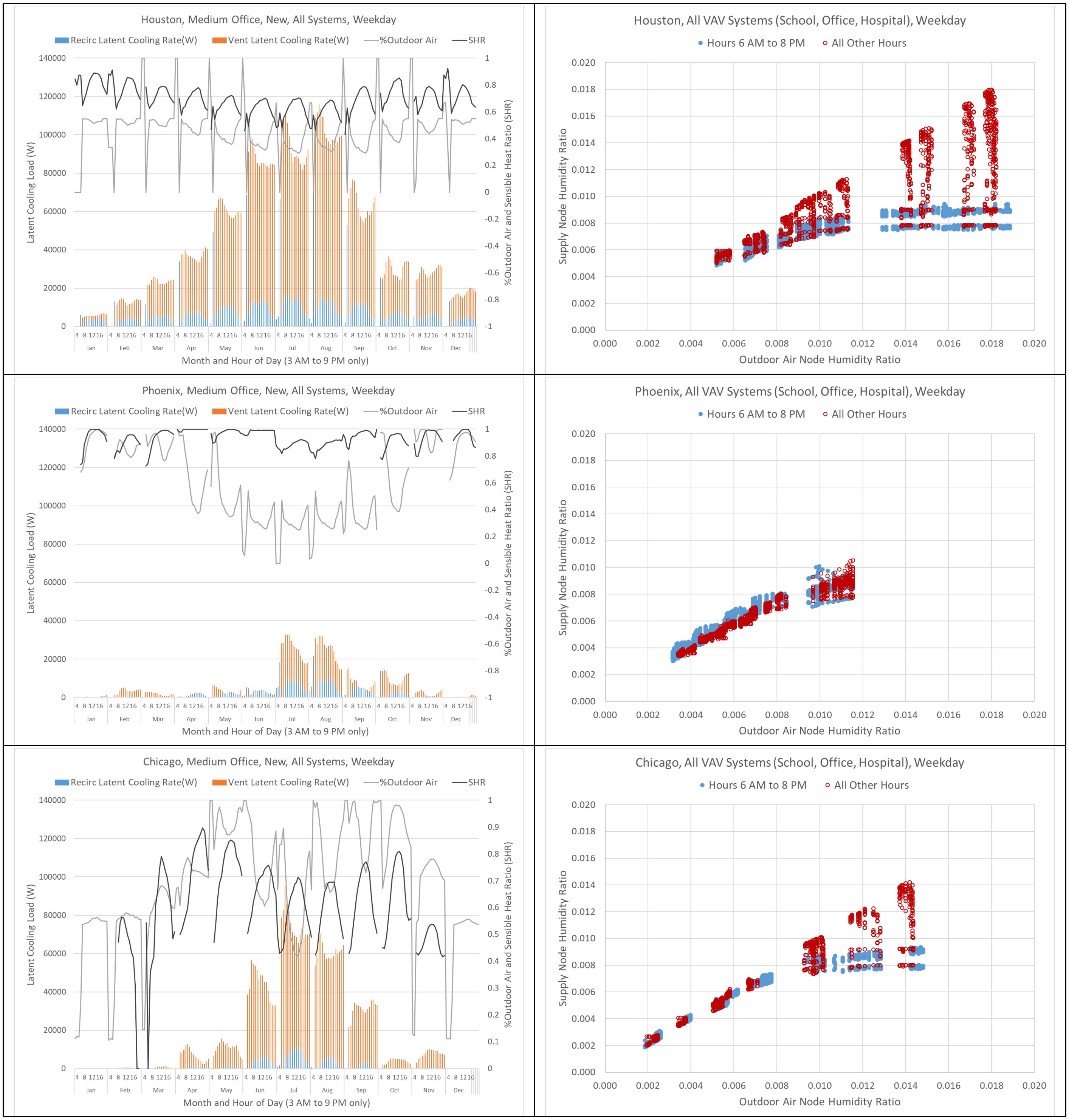


Figure 5-5 Latent Loads and Humidity Ratios: Select Building Types in Houston, Phoenix, and Chicago

Figure 5-6 and Figure 5-7 illustrate the dependence on SHR of both total cooling load and the energy used for cooling. In both figures, the data for a single system across all climate zones and hours of the year are used to create the plot. The two systems chosen for these figures are the Medium Office VAV_1 system (which serves the bottom floor), and the Stand-alone Retail PSZ-2 system (which serves the core retail area). The two systems are of comparable size, and the data have not been normalized to per-square-foot in these plots. In Figure 5-6, the total cooling load is plotted against the outdoor air temperature (OAT) for a range of different SHR values. To create this plot, the hourly data are first binned according to the values of OAT and SHR. OAT bin M corresponds to temperatures in the range [M*10, (M+1)*10] degrees Fahrenheit (deg F), and SHR bin N corresponds to SHR values in the range [N*0.1, (N+1)*0.1]. The integer labels on the different curves correspond to the value of N for that SHR bin. On the x-axis, the OAT bin is indicated by the temperature at the bin mid-point. Within each bin the hourly loads are averaged. Figure 5-6 shows that there is a general increase of the total load as SHR decreases, as expected due to the contribution of latent load. What is more interesting is that the curves seem to cluster into two groups, with SHR equal to 0.7 or less, and SHR equal to 0.8 and above. For the low SHR curves, the increase in load as a function of OAT is steeper, and at higher OATs the magnitude of the load difference is quite significant. The pattern is generally the same for both system types.

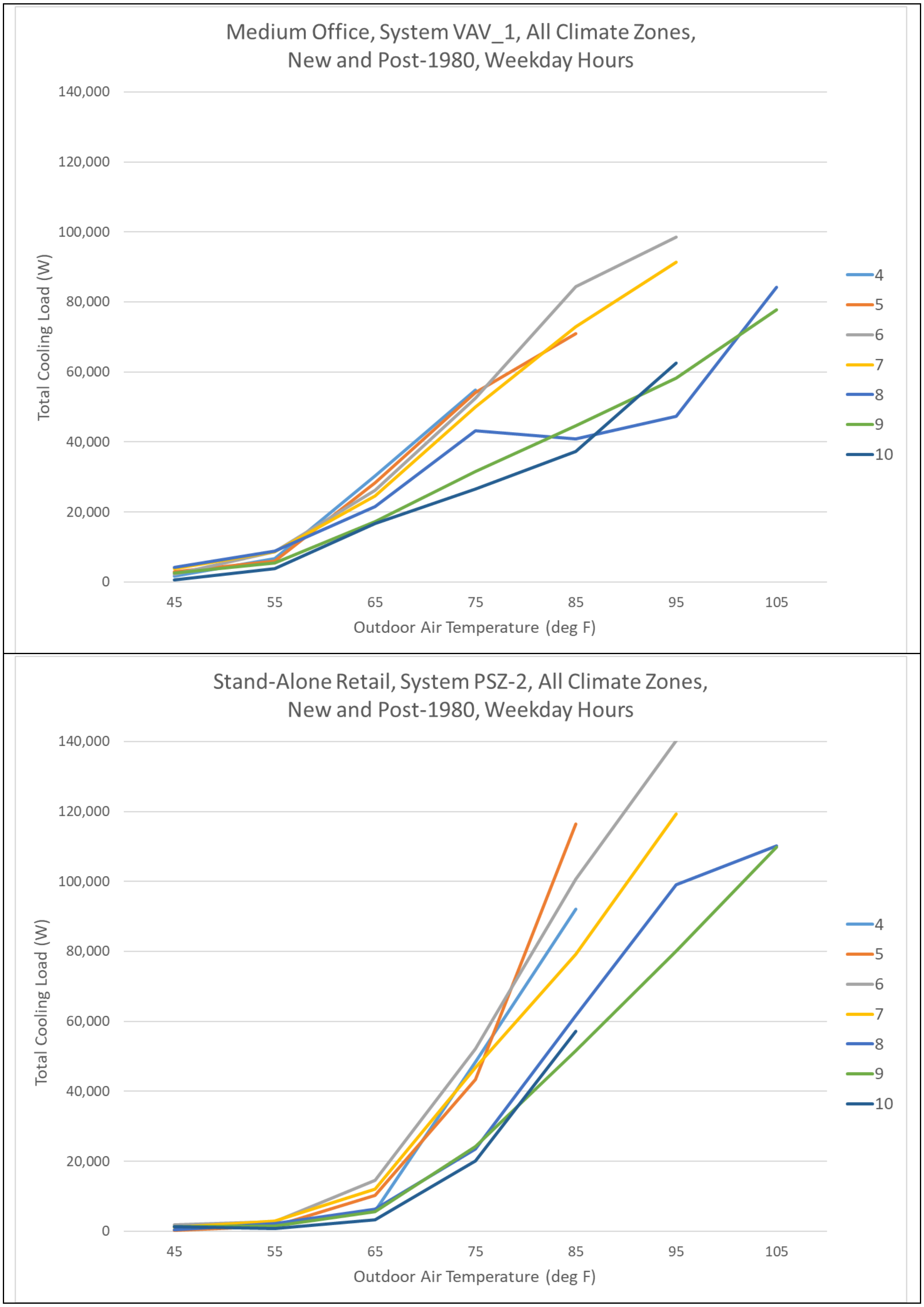


Figure 5-6 Total Cooling Load as a function of Outdoor Air Temperature for various Sensible Heat Ratio bins, Medium Office and Stand-Alone Retail

Figure 5-7 provides a visualization of the way the cooling coil energy use varies with SHR. This figure also illustrates the degree of hourly and seasonal variability that is hidden by the averaging in Figure 5-6. To create Figure 5-7, data are used across all climate zones for the two systems of Figure 5-6. The vertical axis of the scatter plots shows the hourly HVAC energy use for cooling (reported by EnergyPlus), scaled to the maximum value over all the data. The horizontal axis shows the SHR. Each point in the plot represents one hour for one system. To control for temperature conditions, the data are organized into OAT bins. The plot shows hours for which the OAT is between 70-80 deg F as blue dots, and hours for which the OAT is between 80-90 degF as orange dots. To provide a sense of how the OAT and SHR conditions correlated with specific climates, the data for Phoenix are overlaid with open black squares, and the data for Houston are overlaid with open black triangles.

While there is a great deal of scatter in the data, there is a clear trend towards increasing energy use as SHR decreases. The rate of increase is quantified by introducing two regression lines; the equations for these regression lines are provided in the plot (colors of the equations and regression lines coordinate with the markers). The two systems show similar tendencies; in the lower OAT bin, the rate of increase in power use as the SHR decreases is approximately the same for both buildings, but in the higher OAT range the power consumption of the Stand-alone Retail PSZ system is more sensitive to SHR than the VAV system. Overall, for a decrease of SHR from 0.8 to 0.6, the gain in average power consumption, as represented by the regression lines, is 20%-30%.

Figure 5-8 shows the distribution of SHR values (computed on an hourly basis) across a selection of climate zones and building types. The distributions are represented as box-and-whisker plots, with the box width defining the 25th and 75th percentiles of the distribution, the whiskers the 5th and 95th percentiles, and the horizontal line the median. Building types are shown as different colors, and clustered together within a climate zone. The climate zones are represented by Houston, Phoenix, San Francisco, Chicago and Boulder. The plot shows, not surprisingly, that the SHR distributions are similar across dry climates, and across humid climates, irrespective of whether these are hot or cold. Hence, the distributions for Houston and Chicago are very similar, as are those for Phoenix and Boulder. The lower values and broader range of SHR for the Midrise Apartment building reflects the higher ventilation loads (based on occupancy), since, as noted above, latent loads are primarily ventilation driven.

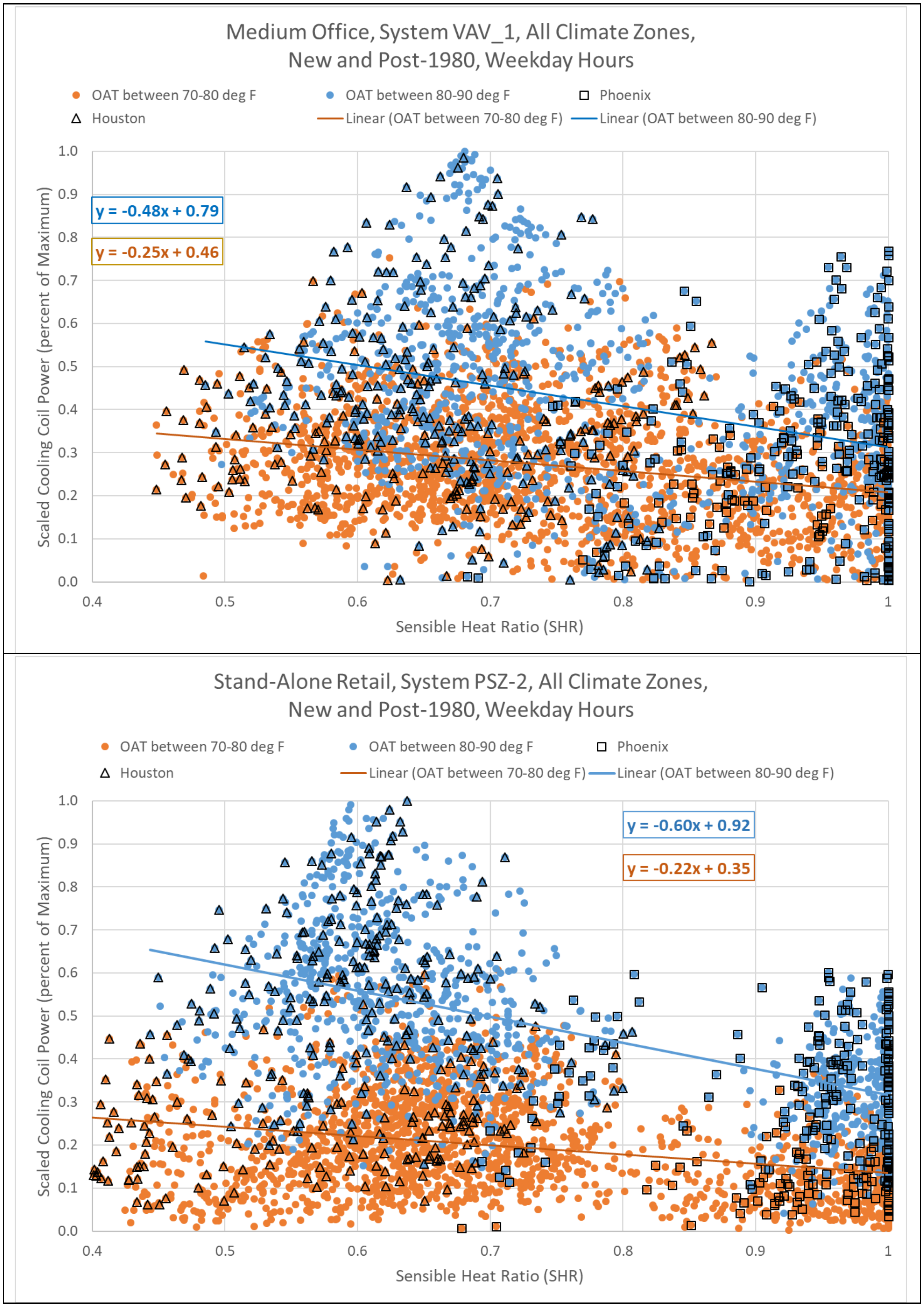


Figure 5-7 Total Cooling Power as a function of Sensible Heat Ratio for two Outdoor Air Temperature bins, Medium Office and Stand-Along Retail

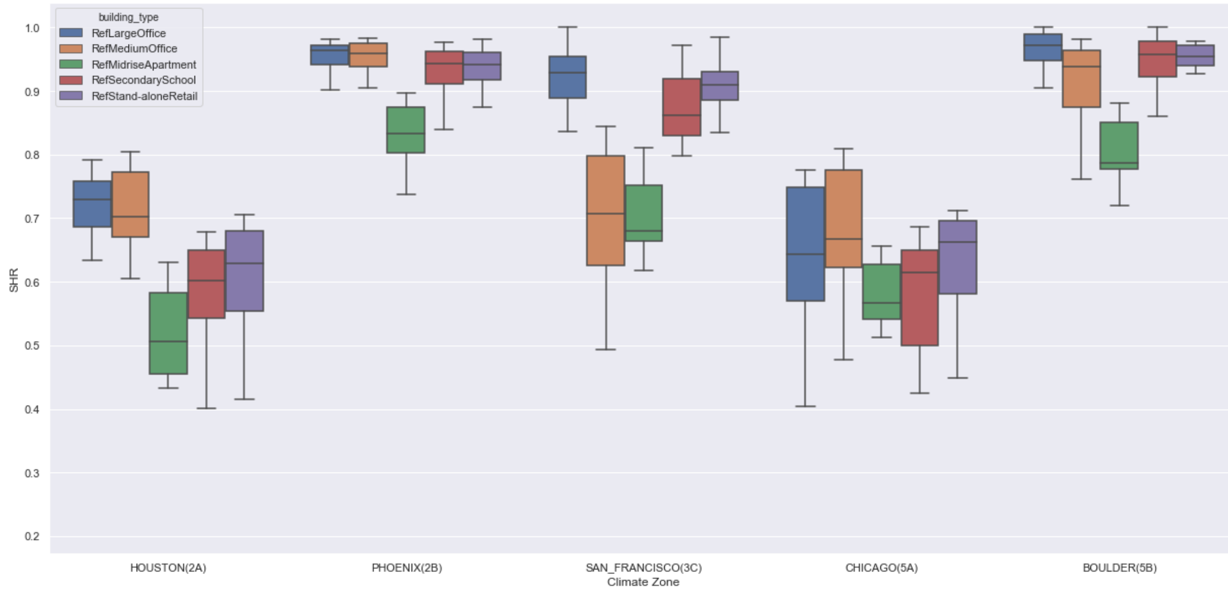


Figure 5-8 Distribution of Sensible Heat Ratios for a Selection of Climate Zones and Building Types

6. *Conclusions*

This report describes the development of a database of space-conditioning loads for commercial buildings, based on prototypes developed for the EnergyPlus simulation software, with a particular focus on cooling loads. The prototypes cover sixteen building types and three vintages, which were simulated in eighteen climate zones. In addition to simply generating the loads, detailed information about air conditions at the appropriate EnergyPlus system nodes to disaggregate the loads into four categories were used: sensible and latent load, each separated into the component due to incoming ventilation air, and the component due to air recirculated from the conditioned zones. These disaggregated loads are calculated for each HVAC system that is present in a building. As stated in Section 2, each vintage of commercial building prototypes has the same set-point temperatures, ventilation rates, HVAC systems, internal loads, and envelope characteristics across the 16 climate zones. While in the actual building stock, building envelopes, HVAC systems, internal loads, and set-points would vary, the disaggregated loads in this report provide a picture of the variation of cooling and heating loads across climate zones.

As noted in the introduction, in a second phase of this project, the results described here will be used to construct a larger sample of loads that reflect a broader range of characteristics in the commercial building stock than are represented in the prototype reference buildings. The disaggregation of the building loads into four components serves this purpose because it reflects real physical differences in the various drivers of space conditioning loads. Loads associated with ventilation air are driven by climate conditions and incoming mass flow; mass flow is correlated to ventilation code requirements based on occupancy, schedule and square footage, and potential use of economizers. The sensible loads associated with recirculated air are driven by envelope gains or losses, lighting and equipment. Building occupancy and infiltration rates affect both recirculated sensible and latent loads.

By correlating variables driving the four component loads with the loads themselves, simple models can be developed to account for changes to the building features, use, or location. For example, a broader range of climates can be modeled simply by adjusting the air conditions of the incoming ventilation air. Changes to the building envelope such as window improvements that reduce solar gain, can be modeled by adjusting the recirculated sensible loads. Changes to either ventilation codes or to building occupancy can be modeled by adjusting the ventilation air mass flow. As each building system is considered separately, the simulation data can also be used to model the diversity of loads on a given equipment type based on the types of zones it serves. More detail on this approach to developing a set of building load characteristics more broadly reflective of the commercial building stock will be described in a second report.

This report has also extensively considered the relative importance of latent loads, for a given building and system, as the climate conditions vary. Both the magnitude of the total load on the system and the system energy use vary significantly in moving from dry to humid climates. This is important because general considerations of building loads often rely on drivers such as cooling degree days that consider only outdoor air temperature, which apply directly only to the sensible loads. To the extent that HVAC systems rely on low coil temperatures to provide any needed dehumidification of ventilation air, the magnitude of latent loads may also constrain the way system designs can be altered to improve efficiency. For example, investigation of different approaches to the removal of latent vs. sensible heat was a major feature of the design finalists for the Global Cooling Prize (Global Cooling Prize 2019).

A data table containing a summary of the load data across all buildings, systems and climates examined for this report is also available in Excel format. The table includes annual, cooling season and heating season values for the four component loads, as well as information on ventilation air flow and other summary data.

References

Briggs et al (2003). Briggs, R.S., R.G. Lucas, T. Taylor. (2003). *Climate Classification for Building Energy Codes and Standards: Part 2 - Zone Definitions, Maps and Comparisons, Technical and Symposium Papers*. ASHRAE Winter Meeting, Chicago, IL. January 2003. Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers. (Last accessed October 2009.) http://resourcecenter.pnl.gov/html/ResourceCenter/1420.html

DOE-BECP (2019). U.S. Department of Energy-Office of Energy Efficiency and Renewable Energy, Building Energy Codes Program. *State Code Adoption Tracking Analysis.* Washington, D.C. (Last Accessed March 13, 2020) https://www.energycodes.gov/state-code-adoption-tracking-analysis

DOE-EERE (2015). U.S. Department of Energy-Office of Energy Efficiency and Renewable Energy. *Direct Final Rule Technical Support Document: Energy Efficiency Program For Consumer Products And Commercial And Industrial Equipment: Small, Large, And Very Large Commercial Package Air Conditioning and Heating Equipment.* Washington, DC. Chapter 7. December 2015.
https://www.regulations.gov/document?D=EERE-2013-BT-STD-0007-0105

DOE-EERE (2018). U.S. Department of Energy-Office of Energy Efficiency and Renewable Energy. *EnergyPlus Version 8.9.0 Documentation, Engineering Reference.* Washington, DC. March 2018. (Last accessed: March 6, 2020)
https://energyplus.net/sites/all/modules/custom/nrel_custom/pdfs/pdfs_v8.9.0/EngineeringReference.pdf

DOE-EERE (2020a). U.S. Department of Energy-Office of Energy Efficiency and Renewable Energy, Building Technology Office. *EnergyPlus*. Washington, DC. (Last accessed February 20, 2020.) https://energyplus.net/

DOE-EERE (2020b). U.S. Department of Energy-Office of Energy Efficiency and Renewable Energy. *Commercial Reference Buildings*. Washington, DC. (Last accessed February 20, 2020.) https://www.energy.gov/eere/buildings/commercial-reference-buildings

DOE-EIA (2012). U.S. Department of Energy-Energy Information Administration. *2012 Commercial Buildings Energy Consumption Survey.* Washington, DC. (Last accessed: March 6, 2020.) https://www.eia.gov/consumption/commercial/data/2012/

DOE-EIA (2014). U.S. Department of Energy-Energy Information Administration. *Commercial Demand Module of the National Energy Modeling System: Model Documentation 2014.* Washington, DC. August 2014. (Last accessed: March 6, 2020.)
https://www.eia.gov/outlooks/aeo/nems/documentation/commercial/pdf/m066(2014).pdf

DOE-EIA (2020). U.S. Department of Energy-Energy Information Administration. *Annual Energy Outlook 2020.* Washington, DC. Release date: January 29, 2020. https://www.eia.gov/outlooks/aeo/

Deru et al (2011). M. Deru, K. Field, D. Studer, K. Benne, B. Griffith, P. Torcellini, B. Liu, M. Halverson, D. Winiarski, M. Rosenberg, M. Yazdanian, J. Huang, and D. Crawley. *U.S. Department of Energy Commercial Reference Building Models of the National Building Stock.* Technical Report NREL/TP-5500-46861. February 2011. National Renewable Energy Laboratory, Golden, CO. https://www.nrel.gov/docs/fy11osti/46861.pdf

Global Cooling Prize (2019). (Last accessed: March 6, 2020.) https://globalcoolingprize.org/about-the-global-cooling-prize/

Williams et al (2013). A. Williams, E. Vine, S. Price, A. Sturges, G. Rosenquist. *The Cost of Enforcing Building Energy Codes: Phase 1.* LBNL-6181E. April 2013. Lawrence Berkeley National Laboratory, Berkeley, CA. https://ees.lbl.gov/publications/cost-enforcing-building-energy-codes